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Handbook of Engineering Systems Design

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With 178 Figures and 54 Tables

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Editors
Anja Maier
Department of Technology
Management and Economics
DTU - Technical University of Denmark
Kongens Lyngby, Denmark

Department of
Design, Manufacturing and
Engineering Management
University of Strathclyde
Glasgow, UK

Josef Oehmen
Department of Technology
Management and Economics
DTU - Technical University of Denmark
Kongens Lyngby, Denmark

Pieter E. Vermaas
Philosophy Department
Delft University of Technology
Delft, The Netherlands

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Preface

The Handbook of Engineering Systems Design provides the first authoritative survey of the state of the art of the engineering systems design perspective, written by leading experts. The Handbook will be a resource for engineering systems design scholars and enable industry practitioners, policymakers and researchers in other fields to discover, apply and further develop the thinking, methods and results. And it is time for learning about and applying the engineering systems perspective: The world is facing a series of challenges which require global effort to overhaul existing technical infrastructures in close synchrony with social transformations in our societies and reforms in institutional governance.

In engineering systems design, technology is seen within a wider socio-technical systems perspective, approaching our world as made up of global engineering systems such as the energy system, the transport system and the healthcare system, which are moreover connected by multiple technical, social and institutional links all over the world. This Handbook provides you with the means to shape these global engineering systems by designing interventions and thus provides a basis for addressing the global challenges.

The Handbook is the result of a joint editorial effort by the Technical University of Denmark (DTU) and the Delft University of Technology (TU Delft), bringing together expert knowledge of the field of engineering systems design within the wider academic and practitioner landscape across the globe. With all scholars who contributed to giving the state of the art in the field, this Handbook unlocks for you the richness and importance of engineering systems design.

July 2022

Anja Maier
Josef Oehmen
Pieter E. Vermaas
Editors

Acknowledgments

This Handbook reflects the importance of thinking in systems and the necessity of designing systems for an equitable, inclusive and sustainably connected world.

As editors, professionally and personally, we wish to thank each and every one of you who we have been in dialogue with over the years on the Handbook of Engineering Systems Design. We thank you for your substantial works and insights, forming long-lasting partnerships and co-creating new field-shaping opportunities: chapter authors, reviewers, research partners, industry partners, policy partners, students, colleagues, funders and our families. With you, this Handbook has come alive, marking a major milestone for the field and providing a platform to evolve forward.

Thank you to the international professional organisations for our dialogue in the form of individual correspondences, group workshops, feedback following presentations at seminars and conferences, author contributions and more. This includes the Council of Engineering Systems Universities (CESUN), the Design Society, the International Council on Systems Engineering (INCOSE), the International Society for the Systems Sciences, acatech – the National Academy of Science and Engineering and ATV – the Danish Academy of Technical Sciences.

We express our sincere gratitude to our universities DTU-Technical University of Denmark, Delft University of Technology and the University of Strathclyde. The work on this book has in many ways been inspired by research and teaching activities with colleagues at our universities as a whole. We are especially grateful for our partnership with DTU Skylab over many years, accelerating the impact of the many purpose-driven real-world system design projects arising through the Holistic Design of Engineering Systems course in the Design and Innovation Programme.

We thank the editorial and production teams for Major Reference Works Springer Reference Nature for our trusting collaboration in shaping engineering systems design.

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About the Editors

Anja Maier
Department of
Technology, Management, and Economics
DTU - Technical University of Denmark
Kongens Lyngby, Denmark

Department of
Design, Manufacturing and
Engineering Management
University of Strathclyde
Glasgow, UK

Anja Maier is Professor of Engineering Systems Design and Head of Department Design, Manufacturing and Engineering Management at the University of Strathclyde. She is also professor at the DTU – Technical University of Denmark, where she has led the Engineering Systems Design research section, conducting interdisciplinary research into designing, building and operating engineering systems. Linking the human and engineering sides in systems design with a focus on studying and supporting human behaviour, her research results have had a direct impact on the design and development of automobile and aero engines, healthcare services, medical devices and cleantech networks. In particular, her work on system design process maturity and capability maturity assessment methods is frequently cited. She serves on the Board of Management of the worldwide Design Society, on the Editorial Board of the *Journal of Engineering Design* and as Associate Editor of the *Design Science Journal*. She is a Member of the International Council on Systems Engineering (INCOSE), a Fellow of the Cambridge Philosophical Society, of the National Academy of Science and

Engineering (acatech), Germany, and of the National Academy of Technical Sciences (ATV), Denmark.

Josef Oehmen
Department of
Technology, Management, and Economics
DTU - Technical University of Denmark
Kongens Lyngby, Denmark

Josef Oehmen is Associate Professor at DTU – Technical University of Denmark, Engineering Systems Design research section. His research focuses on managing large-scale engineering programmes, especially on the management of risk and resilience. He teaches engineering design, project management and risk management at the graduate and post-graduate level. He has worked with over 100 organisations to improve their engineering strategy and execution. He is the founder and coordinator of the DTU RiskLab, co-founded DTUs Engineering Systems Design research section and founded MITs Consortium for Engineering Program Excellence. Prior to DTU, he worked at MIT and ETH Zurich, where he also obtained his PhD. He led working groups at both the Design Society and INCOSE and was one of the early drivers behind INCOSE's and PMI's ongoing strategic cooperation on engineering programme management.

Pieter Vermaas
Philosophy Department
Delft University of Technology
Delft, The Netherlands

Pieter Vermaas is Associate Professor at the Ethics and Philosophy Department of Delft University of Technology. His current research in the philosophy of technology focuses on quantum technologies and design methodology. Research on quantum technologies concern their emergence and impact on society and on our understanding of quantum physics. Research on design includes analysis and validation of design methods within the traditional domains of engineering, product development and architecture as well as in business, policy and the social realm. This research builds on earlier analytic projects on engineering and on the concepts of technical artefact and technical function. These projects have resulted in an action-theoretical analysis of the design and use of artefacts, a philosophical account of technical functions called the ICE theory (*Technical Functions*, Springer, 2010) as well as a textbook on the philosophy of technology (*A Philosophy of Technology*, Morgan and Claypool, 2011) and a handbook with Springer Nature on Ethics, Values and Technological Design (Springer, 2015). Vermaas is Editor-in-Chief of the Springer Nature book series *Philosophy of Engineering and Technology.*

Contributors

Faez Ahmed Design Computation and Digital Engineering Laboratory, MIT, Cambridge, MA, USA

Petra Badke-Schaub Department of Design, Organisation and Strategy, Delft University of Technology, Delft, Netherlands

Pieter W. G. Bots Faculty of Technology, Policy and Management, Delft University of Technology, Delft, The Netherlands

Ole Broberg Department of Technology, Management and Economics, DTU-Technical University of Denmark, Kongens Lyngby, Denmark

David A. Broniatowski Department of Engineering Management and Systems Engineering, The George Washington University, Washington, DC, USA

Maude Brunet Department of Management, HEC Montreal, Montreal, Canada

Michel-Alexandre Cardin Dyson School of Design Engineering, Imperial College London, London, UK

Centre for Systems Engineering and Innovation, Imperial College London, London, UK

Philip Cash Department of Technology, Management and Economics, DTU-Technical University of Denmark, Kongens Lyngby, Denmark

Wei Chen Integrated Design Automation Laboratory, Northwestern University, Evanston, IL, USA

John Clarkson Department of Engineering, University of Cambridge, Cambridge, UK

Noshir Contractor Jane S. & William J. White Professor of Behavioural Sciences, Science of Networks in Communities Laboratory, Northwestern University, Evanston, IL, USA

Luke Craven School of Business, UNSW, Canberra, Australia

Yaxin Cui Integrated Design Automation Laboratory, Northwestern University, Evanston, IL, USA

Jaap Daalhuizen Department of Technology, Management and Economics, DTU-Technical University of Denmark, Kongens Lyngby, Denmark

Andrew Davies SPRU, University of Sussex Business School, Brighton, UK

Olivier de Weck Engineering Systems Laboratory, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, USA

M. Drewel Heinz Nixdorf Institut, Universität Paderborn, Paderborn, Germany

Roman Dumitrescu Fraunhofer-Institut für Entwurfstechnik Mechatronik IEM, Paderborn, Germany

Claudia Eckert School of Engineering and Innovation, The Open University, Milton Keynes, UK

Amro M. Farid Laboratory for Intelligent Integrated Networks of Engineering Systems, Thayer School of Engineering, Dartmouth Department of Computer Science, Dartmouth College, Hanover, NH, USA

Jürgen Gausemeier Heinz Nixdorf Institut, Universität Paderborn, Paderborn, Germany

Joana Geraldi Department of Organization, Copenhagen Business School, Copenhagen, Denmark

Wiljeana Jackson Glover Operations and Information Management Division and the Kerry Murphy Healey Center for Global Healthcare Entrepreneurship, Babson College, Babson Park, MA, USA

Paul T. Grogan School of Systems and Enterprises, Stevens Institute of Technology, Hoboken, NJ, USA

Michael Z. Hauschild Department of Technology, Management and Economics, DTU-Technical University of Denmark, Kongens Lyngby, Denmark

Andreas M. Hein Centrale Supélec, Laboratoire Genie Industriel, Université Paris Saclay, Gif-sur-Yvette, France

Space Systems Engineering, Centre for Security, Reliability and Trust (SnT), Université du Luxembourg, Luxembourg, Belgium

Rachele Hendricks-Sturrup Duke-Margolis Center for Health Policy, Washington, DC, USA

Paulien Herder Faculty of Applied Sciences, TU Delft, The Netherlands

Babak Heydari College of Engineering and Network Science Institute, Northeastern University, Boston, MA, USA

Björgvin Hjartarson Department of Technology, Management and Economics, DTU-Technical University of Denmark, Kongens Lyngby, Denmark

Ola Isaksson Department of Industrial and Materials Science, Chalmers University of Technology, Gothenburg, Sweden

Marija Jankovic Centrale Supélec, Laboratoire Genie Industriel, Université Paris Saclay, Gif-sur-Yvette, France

Misha Kaur School of Business, UNSW, Canberra, Australia

Igor Kozine Department of Technology, Management and Economics, DTU-Technical University of Denmark, Kongens Lyngby, Denmark

Southern University of Denmark, Odense, Denmark

Susan Krumdieck School of Energy, Geoscience, Infrastructure and Society, Islands Centre for Net Zero, Heriot-Watt University, Edinburgh, UK

Jan Kwakkel Faculty of Technology, Policy and Management, Delft University of Technology (TU Delft), Delft, Netherlands

Peter Lloyd Department of Design, Organisation and Strategy, Faculty of Industrial Design Engineering, Delft University of Technology, Delft, The Netherlands

Anja Maier Department of Technology, Management and Economics, DTU-Technical University of Denmark, Kongens Lyngby, Denmark

Department of Design, Manufacturing and Engineering Management, University of Strathclyde, Glasgow, UK

Mo Mansouri School of Systems and Enterprises, Stevens Institute of Technology, Hoboken, NJ, USA

Department of Science and Industry Systems, University of South-Eastern Norway, Kongsberg, Norway

Tim C. McAloone Department of Civil and Mechanical Engineering, DTU-Technical University of Denmark, Kongens Lyngby, Denmark

Alison McKay Socio-Technical Centre and School of Mechanical Engineering, University of Leeds, Leeds, UK

Chris McMahon School of Civil, Aerospace and Mechanical Engineering, University of Bristol, Bristol, UK

Department of Civil and Mechanical Engineering, DTU-Technical University of Denmark, Kongens Lyngby, Denmark

Sebastiaan Meijer Department of Biomedical Engineering and Health Systems, KTH Royal Institute of Technology, Stockholm, Sweden

Ana Mijic Department of Civil and Environmental Engineering, Imperial College London, London, UK

Centre for Systems Engineering and Innovation, Imperial College London, London, UK

James Moultrie Department of Engineering, University of Cambridge, Cambridge, UK

Josef Oehmen Department of Technology, Management and Economics, DTU-Technical University of Denmark, Kongens Lyngby, Denmark

Karol Olejniczak Institute of Social Sciences, SWPS University of Social Sciences and Humanities, Warsaw, Poland

Jitesh H. Panchal School of Mechanical Engineering, Purdue University, West Lafayette, IN, USA

Panos Y. Papalambros Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI, USA

Rebecca Anne Price Department of Design, Organisation and Strategy, Faculty of Industrial Design Engineering, Delft University of Technology, Delft, The Netherlands

Jayanth Raghothama Department of Biomedical Engineering and Health Systems, KTH Royal Institute of Technology, Stockholm, Sweden

Donna H. Rhodes Sociotechnical Systems Research Center, Massachusetts Institute of Technology, Cambridge, MA, USA

Mark A. Robinson Socio-Technical Centre and School of Mechanical Engineering, University of Leeds, Leeds, UK

Alejandro Romero-Torres Department of Management, University of Quebec in Montreal, Montreal, Canada

Adam M. Ross Sociotechnical Systems Research Center, Massachusetts Institute of Technology, Cambridge, MA, USA

Harald Schaub Safety and Security Academy IABG, Otto-Friedrich University, Bamberg, Ottobrunn, Germany

Wester C. H. Schoonenberg Laboratory for Intelligent Integrated Networks of Engineering Systems, Thayer School of Engineering, Dartmouth College, Hanover, NH, USA

Zhenghui Sha System Integration and Design Informatics Laboratory, The University of Texas at Austin, Austin, TX, USA

Dieter Spath acatech - Deutsche Akademie der Technikwissenschaften. National Academy for Science and Engineering, Munich, Germany

Institute of Human Factors and Technology Management (IAT), University of Stuttgart, Stuttgart, Germany

Steffen Steglich acatech - Deutsche Akademie der Technikwissenschaften. National Academy for Science and Engineering, Munich, Germany

Mario Štorga Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Zagreb, Croatia

Department of Business Administration, Technology and Social Sciences, Luleå University of Technology, Luleå, Sweden

Brendan P. Sullivan Department of Design, Production and Management, University of Twente, Enschede, Netherlands

Zoe Szajnfarber Department of Engineering Management and Systems Engineering, The George Washington University, Washington, DC, USA

J. Robert Taylor Department of Technology, Management and Economics, DTU-Technical University of Denmark, Kongens Lyngby, Denmark

Christian Thuesen Department of Technology, Management and Economics, DTU-Technical University of Denmark, Kongens Lyngby, Denmark

Ricardo Valerdi Department of Systems & Industrial Engineering, University of Arizona, Tucson, AZ, USA

Pieter E. Vermaas Philosophy Department, Delft University of Technology, Delft, The Netherlands

Jennifer Whyte Department of Civil and Environmental Engineering, Imperial College London, London, UK

Centre for Systems Engineering and Innovation, Imperial College London, London, UK

School of Project Management, The University of Sydney, Sydney, Australia

Johannes Winter acatech - Deutsche Akademie der Technikwissenschaften. National Academy for Science and Engineering, Munich, Germany

David C. Wynn Department of Mechanical and Mechatronics Engineering, University of Auckland, Auckland, New Zealand

Markus Zimmermann Laboratory for Product Development and Lightweight Design, TUM School of Engineering and Design, Technical University of Munich, Munich, Germany

Part I

The Engineering Systems Perspective

Introducing Engineering Systems Design: A New Engineering Perspective on the Challenges of Our Times

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Anja Maier, Josef Oehmen, and Pieter E. Vermaas

Contents

A. Maier (✉)
Department of Technology, Management and Economics, DTU-Technical University of Denmark, Kongens Lyngby, Denmark

Department of Design, Manufacturing and Engineering Management, University of Strathclyde, Glasgow, UK
e-mail: amai@dtu.dk; anja.maier@strath.ac.uk

J. Oehmen
Department of Technology, Management and Economics, DTU-Technical University of Denmark, Kongens Lyngby, Denmark
e-mail: jooehm@dtu.dk

P. E. Vermaas
Philosophy Department, Delft University of Technology, Delft, The Netherlands
e-mail: p.e.vermaas@tudelft.nl

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Abstract

Framing and understanding our connected and evolving world requires a systems perspective. Intervening and acting towards more sustainable futures and a humane society requires (re-)designing. To achieve that, the Handbook of Engineering Systems Design focuses on socio-technical engineering systems shaping our modern lives. Such systems are fulfilling core functions in society and are characterised by a high degree of technical and organisational complexity, multifacetedness of human behaviour, elaborated processes, and long lifecycles. Examples include generating and distributing energy, enabling global communication networks, creating affordable healthcare, managing global digital manufacturing and supply chains, or building and maintaining critical infrastructure. The Handbook is an authoritative compendium and reference source written by leading experts in the field from across the globe. It is written for scholars as well as practitioners transforming society through research, education, industry, and policy and as such, an essential resource for decision makers to understand their role as change makers. In this introduction, the core terms of the engineering systems approach are defined and the current context in which engineers work is described, characterised by the developments of globalisation and interconnectedness and by the challenges of sustainability and digitalisation. The introduction then focuses on interventions in engineering systems by design, looks at advantages and some concerns of adopting the engineering systems approach, poses open questions for the future, including a call to action for training the ability to connect – *connectability* – and provides a summary of the contents of the contributions to the five parts of the Handbook.

Keywords

Digitalisation · Engineering systems · Engineering systems design · Interventions · Societal transformation · Sustainability · Systems thinking

Introduction: Creating a Humane Society

Society seems to be stuck with effectively addressing, moving on, and resolving the major problems of our times. Production and consumption are too high for being maintained by the Earth and efforts to adapt to sustainable levels need proper appreciation of the interconnected nature of our world. All is interconnected – in nature, in engineering, in societies – and any effort to change one part to improve society is therefore typically affected by and affecting multiple feedback- and feedforward loops, including potential rebound effects in other parts of the world. The proposition advanced in this Handbook of Engineering Systems Design is that engineering is creating the means to navigate and cut through this impasse and to achieve societal transitions. Engineering researchers and practitioners have developed an engineering systems perspective on our world by which changes can be realised through design interventions in these engineering systems. In this Handbook we have collected the state of the art about this novel and urgently needed design approach to interventions in sociotechnical engineering systems, and can now share it with engineers, researchers and policy makers to improve our societies.

Our current world is one that is to a large extent shaped and maintained by engineers (Subrahmanian et al. 2018) with the aim of creating a humane society (Simon 1981: 162). Our food, our clothes, our buildings, our transport and communication devices, and much more, are made available and maintained by applications of technologies developed by engineers. As a species we have been prospering with these engineering efforts, as our welfare, our life-expectancy and the number of people living on Earth have continuously risen in the last centuries. These rises have in turn led to new problems, which are currently deepening with climate change and the depletion of resources.

We find ourselves in a dilemma. On the one hand, the world appears to be stuck when we try to improve it. Production is complex, consumption habitually entrenched, and demand and disparity are high. On the other hand, we need to move fast and in informed directions. Our annual demand has for some time already exceeded what the Earth can renew in a year. This ecological overshoot had in 2008 reached a 50% deficit, meaning that it takes the Earth 1.5 years to generate the renewable resources that people use and absorb the CO_2 waste they produce, in 1 year. And some resources will be depleted for good. The consequences of excess greenhouse gases in the atmosphere are clearly noticeable. Climate change and ocean acidification places additional stress on biodiversity and ecosystems, which in turn has direct impact on depletion of life space.

These and other major societal challenges of our time – climate change, food security, financial security, health inequities – cannot be understood in isolation. They are systemic problems and opportunities, meaning that they are all interconnected and interdependent. And from a systemic point of view, a sustainable society needs to be designed in such a way that our ways of consuming and producing, physical infrastructures, and technologies are in accordance with nature's inherent ability to sustain life (Capra and Luisi 2012). And if it was not clear before, latest now has the COVID-19 pandemic shown us vividly and morbidly how crucial it is to take a systems perspective and to design in agreement among nations if we are to solve such worldwide problems. There could not be a more important moment in our life paths.

Engineers have been expected to contribute to dealing with these challenges with new technological applications and innovations. Ever since the industrial revolution, concepts of growth and the trajectory of accelerated growth have become the ruling idea of this age, with technology playing a central role. With promises and hopes set on technology, we also observe that it is increasingly difficult for engineers to offer improvements. The twenty-first century brings an increased recognition that engineers have a harder time to live up the expectations to contribute to resolving our current challenges. The technological fabric that has been put in place is to a large extent causing climate change and the depletion of resources. This fabric is moreover resisting interventions to swiftly transform it to one that is more sustainable. Our world seems locked in its current technological fabric and in the problems it creates, and engineers lack efficient means to break this (dead)lock. What is expected of an engineer is much more than ever, some refer to a new breed of engineers or perhaps engineers in new roles, where engineers are required to be technically savvy, socially savvy, ethically savvy, business savvy, finance savvy, laws and regulations savvy, and more (Douglas et al. 2010).

Our proposition is that engineering is creating the means to live up to these expectations. Engineering researchers and practitioners have developed an engineering systems perspective on our world by which change can be realised through design interventions in these engineering systems. This continues our proud tradition of increasing our engineering capabilities: From devising artefacts that require the expertise of multiple experts, such as the first cars, to complex systems being built from multiple interconnected components, such as our transportation and supply chain system, to, finally, engineering systems that represent the socio-technological infrastructure our society rests on, for example advanced renewable energy grids. As expressed by some of our colleagues: *"Today, in the epoch of engineering systems, we can see an increasing recognition among engineers that beyond the need for more complex and sophisticated technical analysis, even more is required to solve real problems."* (De Weck et al. 2011: 27/28)

This Handbook collects state of the art knowledge and practices about analysing the current sociotechnical fabric of our world and about design interventions that can transform that fabric. The central perspective in this body of knowledge is to understand the technological fabric in terms of sociotechnical engineering systems. Engineering systems are *"systems characterized by a high degree of technical complexity, social intricacy, and elaborated processes, aimed at fulfilling important functions in society"* (De Weck et al. 2011: 31). The Handbook of Engineering Systems Design has contributions that employ this engineering systems perspective for collecting ways to designing effective interventions in the fabric. Seen in that way, the boundary between physical structures and the design of social systems dissolves almost completely (Simon 1981: 175).

To create a humane society, sociotechnical means focus on (1) humans and technology, (2) social contexts with social, political, and economic considerations emphasising societal values, (3) understanding socio-political- and regulatory contexts, and (4) ethical education, including empathy for the environment. In this way the Handbook gives new means to engineers and policy makers to again meet the expectations to address the wicked problems our world is facing, ultimately to create whole systems change, to create societal transitions and transformations.

Designing has been acknowledged as a bridge-builder between technology and humanity (Dorst 2019: 119), and rather than creating specific fixes focusing on addressing complex problem situations with a view toward system transformation. Designing in this Handbook is focusing on interventions, on re-designing, on giving impulses whilst being cognisant of the larger picture. We increasingly observe and read about the need for embedding systems thinking as early as possible in people's lives, and we see a heightened awareness and emphasis of governments to speak about systems problems and to accredit engineers in particular as the ones who think in systems; all in all calling for taking a whole systems design approach to tackling wicked problems such as climate change and efforts towards net zero or net positive (National Engineering Policy Centre 2020). This is the time for systems thinkers and design doers.

In this introduction to the Handbook of Engineering Systems Design we continue with introducing the core terms of the engineering systems approach. Then in section "The Current Context" we describe the current context in which engineers work, characterised by the developments of globalisation and connectedness, and by the challenges of sustainability and digitalisation. In section "Interventions in Engineering Systems: By Design" we focus on designing interventions in engineering systems. Section "Advantages, Concerns, and a Look to the Future of Engineering Systems Design" looks at advantages and some concerns of adopting the engineering systems approach, and poses open questions for the future. An overview of the contents of the different contributions to the Handbook is given in section "Content: The State of the Art of Engineering Systems Design in Five Parts."

Core Terms

The proposition that meaningful change can be realised by designing interventions in engineering systems can be unpacked in two compatible ways. The first is that it means taking the world as consisting of interconnected engineering systems, such as (global) energy, infrastructure, and health systems, and arriving at change by designing interventions in these systems. The second way is to understand the proposition as advancing an engineering systems perspective in which the world is taken as consisting of technology, people, and processes. This means simultaneously considering designing and managing businesses, policy and technology. Both understandings have the underlying assumption of thinking in systems when designing, i.e. focusing attention on the relationships among the entities that make up the system and focusing on the knock-on effects when intervening (Meadows and Wright 2008). We find these throughout the Handbook. The core terms are described next.

Engineering Systems

Engineering systems are defined as complex sociotechnical systems that increasingly shape modern lives. It is our ambition to understand and improve the ways in which we can design and manage and policy navigate these systems. *Engineering systems* are complex sociotechnical systems that provide solutions to central economic and societal challenges, fulfil important functions in society and exist over long lifespans during which they continue to evolve. As such, *"they are partially designed and partially evolved"* (De Weck et al. 2011: 31). Such systems are characterised by core challenges, including technical and organisational complexity, multifacetedness of human behaviour, and uncertainty of long-life cycles. Examples include energy generation and distribution, building and maintaining critical infrastructure, global manufacturing and supply chains, transportation of people and cargo, healthcare delivery, and global communication. By a strict understanding *engineering systems* are large scale global systems. Comprised of many constituent systems, products, and services, these systems continuously evolve. In the chapters in this Handbook, scoping to more "local" examples of such complex sociotechnical systems may be included, such as designing and operating solar energy systems or autonomous vehicles. To reconnect to the global nature of engineering systems, such examples are discussed from an engineering systems perspective, by analysing them as embedded in global systems of systems.

The Engineering Systems Perspective

The engineering systems perspective involves technology, processes, and policies, and is based on systems thinking. Taking an engineering systems perspective means focusing on connections. Eliciting and understanding connections, e.g., by using (re-)framing, mapping, modelling, analysis-, and synthesis methods and tools, enables bringing the anticipation of unintended consequences to the fore (Sillitto 2014) and as such enables emerging properties to be taken into consideration. For example, it can help to understand the consequences of bringing new and uncertain technologies into current system set-ups, to develop scenarios for envisaging how consumer behaviour can impact systems, and to identify how feedback loops can create dynamics. Taking an engineering systems perspective allows us to address complex challenges in holistic and structured ways. What this means in practice is that emphasis is placed on recognising connections, such as technical, social, or economic. It means further that we are actively asked to be aware of the boundaries that we draw, that we are actively asked to map which factors influence across boundaries, and the scope of the system (s) that we are going to take into consideration. Taking a systems perspective means to think of different influences and different drivers. It means to engage multiple disciplines – from the natural sciences, technology, engineering, social sciences, and humanities – to highlight connections between the domains and also to engage multiple stakeholders across science, business, government, and citizen groups. It means encouraging that multiple views are elicited and engaging people who know the detail while retaining the bigger picture. It means combining multiple fields of professional knowledge and integration of multiple stakeholders' interests and expertise (technological, financial, regulatory, legal, ethical, workforce, and public-facing stakeholders). This does, however, not mean to take everything and everyone into account. Yet, it means to be cognisant of the connections and potential knock-on effects an intervention will create, also over time.

Engineering Systems Design Interventions

Designing in this Handbook is understood as *"devising courses of action that change existing situations into desired situations"* (Simon 1981: 129), and thereby as making change in societies (VanPatter 2021: 34/35). As such, the Handbook emphasises designing as change making, going beyond mere problem-solving to creating opportunities. Designing itself is moving from problem formulation or problem solving to reframing what we do as a task of system transformation (Dorst 2019: 117). Designing is central in humankinds' relationship with the artificial world and the natural world. Designing is understood here to go beyond technologies, products, services, to being open to engaging with the large-scale challenges in an ever moving world (Jones 2014; Norman and Stappers 2015).

Any intervention we are making, any initiative we are starting is in some shape or form designing. The complex situations this Handbook addresses require designing with a systems perspective. The onus is on all of us to be aware of designing interactions, of seeing connections, of seeing propagation impact pathways, of seeing potential implications. This will also mean that the paradigm of getting it right first time is impossible and in fact a barrier. The world is dynamic and evolving. Engineering systems designing as working through the impact of any kind of intervention in any kind of context means conceptualising, prototyping locally, thinking globally, modelling, simulating various scenarios and impact paths as ways forward.

The chapters and structure of the Handbook bears the underlying emphasis of *designing interventions*. Why the focus on 'interventions' in engineering systems and interventions from an engineering systems perspective? One of the arguments in this book is that no one ever designs an entire engineering system (Züst and Troxler 2006: 12). Say, we do not tear down our energy and transportation system, to then rebuild an integrated smart grid with all-electric transportation. We only ever design an aspect of the system: in practically all cases, designing will consist of modifications or extensions to some existing element. Hence, we say engineering systems design is essentially designing these specific interventions as levers that move the overall system into the direction we want it to go, which usually requires a model and understanding that spans several interventions and their interactions. Interventions can be seen as efforts or action(s) intended to secure a desired outcome or to change an outcome.

In summary, with a systems perspective, we learn a lot about understanding a situation and mapping the landscape of influences and with designing, we learn a lot about the practical ways to take action and to build prototypes getting us closer to solutions that will make a difference. But it needs a structured framework that people can use that gets them to think deeply, to care about the 'problem', to understand the systems and then re-design solutions within their sphere of influence, and to being cognisant of potential knock-on effects, intended or else. In other words, a systems perspective brings the connections and designing brings action and reflection. Designing with a systems perspective combines ways of seeing plus ways of doing, to get us beyond understanding, to get us going.

The Current Context

The importance to adopt an engineering systems perspective in changing the world can be introduced by considering the current state of technology in the world, that is, the current context engineers work in. This context can be captured by two overall developments that are taking place in the application of technology and by two challenges that technology is facing today. These two developments are shifts from local to global and from separated to interconnected. These developments are to some extent sequential but cumulative, and are resulting into the interlinking of virtually all applications of technology. And it is this interlinking that makes the engineering systems perspective a powerful perspective to understand our current technological fabric. Against this background, the two overall challenges engineers face today are that of sustainability and of digitalisation. The problems of climate change and of the depletion of resources caused by the current technological fabric have to be dealt with urgently, and digitalisation is seen as a necessary step in making the manufacturing of new applications of technology more efficient and sustainable.

Two Connected Developments: From Local to Global and from Separated to Interconnected

The first overall development we witness today is from local to global. Approaching our problems and challenges in a local fashion alone will not be without global ramifications. And conversely, global developments have significant local impacts. In the past, improvements of human existence or increases of productivity were typically realised by local solutions. Technology offered such solutions and for that we developed mechanical engineering and later software engineering and mechatronic engineering approaches for providing one solution at a time: agricultural and construction equipment, steam engines, combustion engines, automotive industry, and aerospace and defence systems. Or changes in behaviour offered solutions to our problems, as crop rotation, hygiene policies, workflow management, and service design. It became clear that these two approaches of technology development and behavioural change were interdependent, leading to a merger of technology and human behaviour, reaching a new category of complexity in engineering. This pushed us into the realm of technical systems engineering, where technology and their operators, regulators, and users collaborate in complex sociotechnical systems that are developed, managed, and maintained with the combined competence of experts from a broad variety of fields in engineering and the social sciences. We are now witnessing the rise of a new era in our approach to problems and challenges – or perhaps we should rather say our approach to creating opportunities and transformations – that requires us to reconcile local and global developments and design decisions.

The second development is that our already highly complex sociotechnical systems stop to be separated systems by becoming co-dependent on one another and functionally as well as technically highly integrated. For example, logistics operations no longer only depend on land, air and sea transport systems, but also on space-based satellite positioning systems. Healthcare relies nowadays on professional human care and policy, as well as on high tech chemistry and ICT systems. And the automotive sector is now becoming a major factor in making our energy system more sustainable by load levelling of electricity demands. Nowadays, products and services are becoming increasingly embedded in systems consisting of technical artefacts, humans and social organisations. These systems are socio-technical engineering systems. The design of a new product or service or experience is not anymore just a local change but also a global engineering system change. Many of the problems we currently face is requiring global changes to engineering systems.

The underlying mechanism is the interconnectedness and truly global nature of our problems and challenges: Starting with nuclear arms introducing us to the idea of a global Armageddon, we have now realised that we all share the same climate, the same natural resources, a highly integrated economical system and our responsibility for global sustainability goals. Today, more than ever, we are designing in an era of systems. This drive to the global motivates the sociotechnical engineering systems perspective. Engineering systems are partially designed, partially evolved (De Weck et al. 2011: 31) integrations of already highly complex systems, for example by integrating the energy and transport systems, to enable sustainable transport (i.e., electrification of transport) as well as sustainable energy generation (i.e., buffering electricity by utilising capacity of transportation system).

System interconnectedness becomes especially tangible in emergency situations or adverse incidents where system responses and various uncertainties can be observed. Two examples from energy and food follow:

Electricity system failures are pushing the resilience of electricity systems due to knock-on effects to other systems, with energy networks such as electricity, heat, gas as linked also to transport- and communication networks. To illustrate interconnectedness, an example of a system failure is the UK August 2019 transmission system frequency event, which saw more than a million customers disconnected from the electricity system. In this event one generator came of the electrical system for good reasons but created issues with voltage that in turn caused other equipment hick-ups. This perturbation then caused trains to stop, and these trains could not move again when the power got back on, needing real people to start them up again (MacIver et al. 2021).

Interconnectedness can also mean that a systemic solution might have the potential to address and potentially solve multiple problems simultaneously. Illustrating with an example from the food sector, one might for instance envisage change from large-scale industrial, chemical agriculture to community-based, organic, sustainable farming. It would contribute to solving three of our biggest problems: reduce our energy dependence, healthy, organically grown food would have a positive effect on public health as many chronic diseases are linked to our diet, and organic farming would contribute significantly to fighting climate change because organic carbon-rich soil would draw more CO_2 from the atmosphere (Capra and Luisi 2012).

The implications of separate engineering systems becoming increasingly interconnected is that the design of interventions in one engineering system becomes dependent not just on the current technological state and social constellation in that specific engineering system but also on (changes in) the technological state and social constellations of other interconnected engineering systems. And many of the inabilities we currently have with resolving problems – and paradoxically precisely also the levers we currently have – are due to the interconnectedness of engineering systems, with unintended knock-on and knock-back effects of changes in one engineering system cascading through other engineering systems. Causality is not anymore seen as a directional effect, but as a bidirectional one, moving from connectedness, to interdependence, to interconnectedness.

Two Current Challenges: Sustainability and Digitalisation

Both sustainability and digitalisation present new and unique challenges – as well as new and unique opportunities. Conversations on sustainability are typically problem-driven: We are exceeding our planetary boundaries, we act socially irresponsibly, and we pursue short-term thinking in our economic decisions. These are framed as the large problem of our time that must be solved – expressed, for example, through the interlinked and nested United Nations Sustainable Development Goals (SDGs) – and we subsequently enact large transformation programs in their pursuit. But they also create new opportunities: organisations that master sustainability – from companies to countries – offer a significantly increased value proposition to their clients. Engineering companies, for example, that can offer you nature-based solutions to mitigate climate change impacts on your house and factory, are creating markets that others cannot even compete in.

While our sustainability challenges stem from our 'success' of industrialisation over the last 200 years, digitalisation has a different history: Conversations on digitalisation typically start with the opportunities it offers in creating new services and experiences, and increasing the productivity of existing ones. Stemming from our need to advance our tools in developing and providing modern engineering and service activities with increased computational power, the conversations today paint pictures of digital twins of not only products, systems, and services, but also of humans and parts of our society in the 'metaverse'. Digitalisation is thus both a tool to increase productivity and accessibility of existing products and services, and also an enabler to create new categories of products, services, and ultimately, experiences. The single most powerful driver of digitalisation is its inherent connectedness – the creation of the internet has reduced digital – not environmental – transaction costs to practically zero. Digitalisation then, however, is also discussed emphasising the challenges it presents: Its global, connected and real-time nature creates novel challenges in shaping a productive public discourse, in fighting crime, in keeping critical infrastructure safe, or in stopping exploitation of vulnerable populations.

Sustainability

This is a decisive decade for the future of a humane society. The stable functioning of Earth systems – including the atmosphere, oceans, forests, waterways, biodiversity and biogeochemical cycles – is a prerequisite for a thriving global society. With the human population set to rise to 9 billion by 2050, sustainable development needs to include the security of people and the planet and show the dynamic interconnections and interdependencies.

We are responsible for the current state of affairs, and so we are also responsible for re-thinking our approach to and managing human and natural resources to address the sustainability challenge. It is increasingly acknowledged that our current technological and social systems are not sustainable, requiring too many resources for their development and maintenance. The challenges to make sociotechnical engineering systems sustainable have to be understood in relation to the two overall developments of engineering systems becoming more global and more interconnected: impacts of technical interventions have in the past not always been sensible or understood or accepted; and this understanding is a precondition to making engineering systems sustainable. Whole systems change has to include changes in behaviour, in infrastructures, in policy, in ethics, and in designing processes for forming collaborative partnerships for achieving the global goals. Sustainability – environmental, social, and economic – has to be seen as a pathway to regeneration where we learn how to give back more than we take. We need regeneration, need recovery, need building back. We need pathways to achieving net zero targets, or even better, to achieving net positive targets. Achieving net zero energy means producing, from renewable resources, as much energy on site as is used over the course of a year. Achieving net positive energy means producing, from renewable resources, more energy on site than is used over the course of a year.

An illustrative example of how a systems perspective linking engineering and technology, behaviour, and policy is necessary is the challenge of low carbon energy, thinking across energy production, distribution, storage, and consumption. A whole systems approach to decarbonisation is being advocated (National Engineering Policy Centre 2020), with the energy system sitting within a wider system of multiple social-, technical and environmental factors. A lot of reduction we have seen is through the supply side, through technology measures. Yet, further reduction depends on change in the demand side and that depends on societal or behavioural changes. This can be challenging especially when there can be conflicts between individual goals, such as energy provision and climate-change prevention (Midgley and Lindhult 2021; Cabrera et al. 2021). If and when we reach a situation where human energy consumption becomes sustainable, it will mean the end of the current situation where new innovations that involve increased energy consumption inevitably play their part in adding to the cumulative effects of carbon emissions and ultimately climate change.

Another example is the challenge of how we might achieve sustainable mobility. Functioning transport systems are one of the key drivers of our prosperity. Yet, the steady rise in demand for mobility is putting an ever-increasing strain on our environment, climate and infrastructure. Finding intelligent, environmentally friendly forms of mobility for the future is a significant challenge. Today, people take mobility for granted. But we can face an enormous challenge: how can we satisfy the ever-increasing demand for transport while simultaneously achieving zero CO_2 emissions? Shall we automate? Shall we optimise mobility behaviour? Shall we increase capacity? Other directions? The point is that different propositions have different consequences. Over the last 250 years, humankind has always succeeded in meeting its growing demand for mobility by pioneering new technologies and building the necessary transport infrastructure. Is this the path we shall continue to follow? The more sophisticated the transport network, the more complex and expensive it is to expand. We might opt for tunnelling underground or taking to the air – with drones for instance. Another proposition might be to restrict access, e.g., stricter regulation by means of road pricing systems? Yet another option may be to enhance energy efficiency. Energy consumption is falling thanks to more efficient combustion engines, hybrid technology and lighter vehicles – and the potential for further efficiency gains is promised. Shall we use the strategy of replacement? If we are to reach our global climate targets, replacing fossil fuels with renewables is a proposal on the table. As such, electromobility, powered by renewable energy presents itself as an option, hydrogen and synthetic fuels produced using renewable energy are another option, yet, it takes a lot of energy to produce hydrogen, and even more to manufacture synthetic fuels.

The core of the matter is to allow for multiple possible paths, including low-tech paths, and to allow for multiple time horizons. The engineering systems perspective encourages thinking through and designing alternative scenarios for the future and *"analysing their sensitivity to errors in the theory and data [. . .] for an acceptable future for the energy and environmental needs of a society"* (Simon 1981: 171).

Digitalisation

One way in which engineering systems become increasingly interconnected is through information and telecommunications technologies (ICT systems). These systems have enabled the modelling of the state of separate engineering systems and the subsequent exchange of information between these systems. This development is currently accelerated for improving the efficiency of engineering systems and for taking up the first challenge of making these systems sustainable. The digitalisation challenge includes making the interconnections of engineering systems manageable.

The world economy as well as societies are going through a digital transformation that goes well beyond computerisation and use of information and telecommunications technologies. Digital transformation as the integration of digital technology into all areas of business and life is fundamentally changing how organisations operate and deliver value. It is also a cultural change that requires organisations to continually challenge the status quo, experiment, and get comfortable with failure. This transformation is creating opportunities and challenges.

Some technological advancements that are opening opportunities include light-speed internet, supplementing existing fibre optic networks, allowing, for example, applications such as telepresence, multiplayer games and musicians playing together online. Thanks to new technologies, especially the Internet of Things (IoT), new concepts such as Digital Twinning have been able to make production for manufacturing companies much easier and more efficient. A Digital Twin is a virtual replica of physical assets, whether this is a product, service, or process. It collects, analyses and monitors data and simulates any potential problems that might occur before they do in reality, saving costs and time needed for maintenance and increasing productivity. The Digital Twin is nowadays an instrumental part of every Smart Factory, and we see applications across many sectors, especially in health. Within smart manufacturing, we see applications for predictive maintenance, accident prevention, tracking and restocking inventory, tracing the product journey, getting real-time feedback and other deep knowledge about the processes inside a plant and industry know-how. An application can learn more or less anything. But it needs a good teacher. And this is where it links to ethics and responsibility. Manufacturing is just one example. Digitalisation of society is pervasive, opening many fundamental questions of resources and responsibility. Whilst digitalisation and digital transformations are by some praised as the saviour, it opens up questions about equity of access, about its connection to socially sustainable futures, of inclusiveness of societies. Digitalisation exposes disparities and also creates new ones. What technology literacy does it take in the future? The dark side is also exposed through increased vulnerabilities, e.g., hacking access into vital infrastructure, increasing the power gap between rich and poor countries, old secrets will become known, impact financial systems, new weapons that should never see the light of day, governments losing their grip on criminal organisations, government becoming less transparent, governments gaining too much control over their citizens, increasing power of large tech companies etc. Digitalisation on human lives with its pervasiveness as never seen before, opens deep questions along the safety/security nexus on ethics and on responsibility.

A central challenge of global and ubiquitous digitalisation is – in a surprising way – its incredible success. Today, our private lives are digital, our workplace is digital, and our critical infrastructure is digital. This has created an entirely new set of risks – cascading cyber-physical safety risks, where ‘digital accidents’ or digital attacks lead to wide-spread physical destruction and loss of human life. It has also created new niches in our existing risk landscape – international crime takes advantage of encrypted real time communication channels, sells drugs and weapons online, exploits vulnerable populations, defrauds pensioners, and blackmails companies and public organisations. What makes digitalisation so powerful – its global network, flexible and open architectures, and instantaneous communication – also makes it dangerous. This creates new design imperatives for enabling and ensuring human-led digitalisation for making digitalisation safe and secure by design.

Interventions in Engineering Systems: By Design

A central proposition advanced in this Handbook is that engineering has developed a sociotechnical engineering systems perspective on our world by which change in our world can be realised through designing interventions in these engineering systems.

Engineering systems design affects technological, environmental, behavioural and as such societal change. One of the essential tasks in designing interventions from a systems perspective is boundary scoping, that is, clearly specifying a system’s boundary to define its scale and scope (De Weck et al. 2011: 51). Demarcating the system is defining the boundaries of that part of the material world that needs to be considered, and establishing how its structures and functions can be changed or stabilised (Züst and Troxler 2006: 51). Boundary scoping is important as we need to understand the knock-on effects and as we also need to re-adjust the means given potentially changing contexts and goals through life. Simon formulates it dynamically we are *"designing without final goals"* (Simon 1981: 185). Especially given today's complex context just sketched above, it is hard to imagine true 'green field design'. We are always building on something, re-designing, engaging in 'brown field design'. Systems are partially (intentionally) designed, partially evolved.

We take the two developments from local to global and separated to connected to imply that engineering in the twenty-first century is about intervening in existing complex situations by multidisciplinary engineering systems design. Designing is doing and designing interventions 'moves' a system, stipulates a modification, a change, and effects. Interventions can take the form of adjusting existing products, services, experiences or incorporating new products and services or experiences into the existing engineering systems fabric. Products and services are seen as interventions themselves. Engineering is therefore in the twenty-first century concerned with complex systems containing technical systems, humans, their behaviour, and their social organisations and regulatory frameworks, which evolve under uncertainty due to their complexity and interconnectedness.

This presents significant challenges: Designing interventions to 'improve' evolved, existing engineering systems; operating and managing them best; and creating sociotechnical solutions that incorporate both complex technical aspects, as well as a wide range of organisational and behavioural aspects. In our considered opinion, engineering systems not only represent a quantitative increase in design and sociotechnical engineering challenges, but also a qualitative one. In the engineering systems perspective, the tasks of designing new solutions should now be seen as designing interventions to existing and 'living' engineering systems. Designing these interventions includes designing technologies, guiding and aligning people that are part of the systems as users, operators and regulators, and proactively responding to national and international policies that are in place or should be put in place for enabling the existence and operation of engineering systems.

And this designing cannot be done from scratch, as the currently operating engineering systems provides critical societal values. Creating autonomous vehicles consists not just of designing a car with intelligent technology for navigation but includes also, for instance, the adjustment of the existing road infrastructure, creations of means for control and trust by users and authorities, and adjustment of insurance practices and liability legislation. Creating autonomous vehicles is therefore better approached as an intervention in the existing transportation-related engineering system, rather than as the design of a new technology. Technology is one essential element within engineering systems, and arguable the element that is currently best understood.

Three elements which need additional consideration for dealing with the challenges of designing, managing and shaping enabling policies of engineering systems are complexity, human behaviour and uncertainty.

That technical complexity impacts organisational complexity is well known since the Apollo programme. However, we do not currently have an answer to the level of both technical as well as (socio-)organisational complexity that we are witnessing in engineering systems. This is compounded by two additional factors. First, human behaviour and its adaptive nature and global stakeholders and their influence create dynamics in and impose constraints on engineering systems additional to technological constraints, and for handling them we need new approaches. Second, we are faced with engineering systems that, arguably, have an indefinite life span, and that by their integration co-evolve with each other. This generates significant uncertainty when adjusting or creating an engineering system for realising new technological opportunities. Redesigning, say, the energy system for making it more sustainable, now requires understanding and controlling shifts in human behaviour and (geo)-politics, as well as developments in related engineering systems as transport.

Advantages, Concerns, and a Look to the Future of Engineering Systems Design

The engineering systems perspective brings significant advantages to designing a more humane world. Yet it also raises concerns and leads to a number of questions. In this section we expand on these advantage and issues.

The Advantages of Taking an Engineering Systems Design Perspective

Taking an engineering systems perspective and aiming at changes by designing interventions in these engineering systems has a number of advantages. It combines holistic ways of seeing and structured ways of doing, and in this way enables industry, academia, policy making and civil society to address the problems our current world is confronted with.

Firstly, an engineering systems perspective gives engineers, policymakers, and others insights into systems and how they operate. It sets systems thinking central in designing, which broadens engineering with systems thinking and as such enables seeing connections and asking the right questions before embarking on solutions. This, in turn, puts emphasis on connections and interactions, such as between technology and human behaviour or between technology and social institutions. Moreover, it emphasises the complexity of and the uncertainty in the development of engineering systems and reminds us all to consider emergent properties and the dynamics of engineering systems over time. What this means is to let go of the hope for well-defined, fixed design briefs. Instead, we need to dare to embrace complex challenges with dynamic situations and constantly moving targets. There is no single way of taking an engineering systems approach. There are multiple methods and tools, yet a shared focus on understanding the whole system, recognising that it is complex, and has emergent properties that arise from the way different elements interact, irrespective of whether the system studied is a company, a city, a rail network, a service, or a whole industry sector. Placing systems thinking at the centre and focusing on connections and dynamics thereby alerts engineers to consider potential side-effects, which can emerge lateral as through knock-on effects in the interconnected engineering systems and can emerge temporal as through longer life cycles of engineering systems.

Secondly, an engineering systems design perspective allows decision makers in industry, academia, policy, and civil society more widely to consider behaviours and interactions between different parts of the system, and how these can combine to affect an outcome. A whole systems approach enables decision makers to understand the complex challenges, e.g., posed by targets that demand designing under resource constraints. Designing engineering systems interventions can be seen a discovery process combining structured approaches quantitative and qualitative to understanding and managing technical and physical factors such as infrastructure and novel or advanced technologies with broader perspectives on regulatory, financial, behavioural and other factors, taking into account complex interactions. Overall, an engineering systems perspective helps to consider technical factors, including material technical infrastructure and helps to realise their embeddedness in social systems of the behaviours, attitudes, institutional structures and social economics. Such sociotechnical relationships influence how the overall system functions and how overall, system behaviour evolves, in both desirable and undesirable ways.

Thirdly, an engineering systems approach offers concrete means for framing and modelling *what-if* scenarios, for anticipating alternative futures and multiple configurations in the network of reinforcing and balancing loops of influencing factors (Sterman 2000). Mapping, modelling, what-if scenario envisaging interconnections are important analytical techniques as part of a systems approach. A model provides the ability to identify the next question, progressively to improve one's understanding and reflecting on the weakness of the model. A model is aid for thinking and understanding. Different areas of specialist knowledge can come together and interdependencies among them can be drawn. For example, with respect to regulatory and commercial structures we are working within and the extent to which they act as barriers to what people have identified of what needs to be done and with respect to what is the scope and responsibilities of institutions and actors to getting things done. This is then used as a working assumption about how an intervention might alter the current situation. Models enhance the quality of democratic decision-making. They can offer cost-benefit analyses of various policy options, manage risk and uncertainty, or predict how economic and social factors might change in the future. Modelling approaches and other design techniques such as scenario planning (for exploring alternative approaches and test policy robustness) and deliberative system mapping. This will build a better understanding of social and behavioural dimensions and how technologies work at scale. Techniques such as system maps help to bring stakeholder views such as citizens in. Understanding citizens' journeys and taking time to understand the dimensions of a situation is as much about the process, thinking about the elements and interactions than it is about the systems map that is drawn and co-created. Techniques such as system maps are tools for engagement and give opportunities for conversations. It is about systems thinking in its broadest sense, not system mapping as a specific technique per se. It is the social activity around system mapping that gets people involved, enables a more co-ordinated strategy, and asks for stewardship of people with the artificial world and the natural world.

Finally, thinking through more local interventions whilst being mindful of global ripple effects, has the advantage for mobilisation through multiple initiatives for systems change. Intervening is giving impulses with a sustainable futures perspective forward.

Some Concerns Regarding Engineering Systems Design

The engineering systems perspective also brings some concerns. We present three and discuss ways to approach them.

A first concern is the tension between the engineering systems perspective and the way we describe innovation. The last few decades have been ones in which many innovations saw the light of day, broadly characterised by digital technologies and servitisation, and punctuated with the introduction of the world wide web, smart phones, and social media. Daily and professional life as we know it today is at many points substantially different to life in the 1980s, and these changes and novelties seem at first sight difficult to capture within the engineering systems perspective. According to De Weck et al. (2011), engineering systems cannot be radically changed by design, for instance since changes are constrained by the legacy of existing structures, software and hardware currently part of these systems. Engineering systems are said to be changing partly by design and partly by evolution, which is also the reason to speak in this Handbook of design interventions in existing engineering systems, rather than of their design from scratch. It follows that innovators, like, say, Thomas Edison, could at most have changed local aspects of existing engineering systems, a conclusion that sits less well with how many of us see innovation.

A response to this concern is a description of technology development in engineering systems that accounts in some way for more standard views on innovation. One option is to criticise the ways in which people see innovation. It may be argued that innovation does not exist of punctuated events in technology development driven by breakthrough inventions or iconic visions. In that response, adopted in, for instance, history of technology (Basalla 1989), innovations are analysed as longer-term accumulations of smaller changes, shifting the focus on series of smaller design interventions: the smartphone is then just the integration of a series of existing functionalities and thus the result of a many earlier designs, rather than a magical gift by Steve Jobs. A second option for a response is to find within accounts of engineering systems the conceptual recourses for capturing the ways in which people standardly see innovation. The concept of tipping point is then a candidate to consider. Initially meant to express those systems that are well manageable at one point can all of a sudden spin out of control, one could apply it also to intentional change. One could argue that a series of design interventions in engineering systems can bring a system to a rapid transition from its existing state to a newly envisaged one. By this second approach, the smartphone is indeed the sum of a series of earlier designs. Yet, when it was presented, this sum of designs had in a short period of time radically impacted on the communication engineering system and by extension, societal interaction patterns.

A second concern may be a return to a naïve optimism with the engineering systems perspective. We started this introduction with noting that humane societies seem to be stuck with effectively addressing the major problems of our times and presented the engineering systems perspective as a way to navigate and cut through the impasse. Yet this proposition should be critically approached. Engineering was throughout the last centuries presented and seen as the way forward to improve the human condition, and in the 1960s even advanced as able to provide solutions to social problems (Weinberg 1967). The term that captures this promise was "technological fix" and soon became, just as the prediction it was based on that (nuclear) technology would create very cheap energy resources, a synonym of engineering hubris and also naivety. The proposition that societal problems can be addressed when taking the engineering systems perspective should not be adopted with similar naïve optimism. Instead, this proposition should be met with a critical approach aimed as evaluating and demarcating where the engineering systems perspective may work and where it may not. Design interventions based on more sophisticated analyses of our world may become more effective in addressing our societal problem, yet notwithstanding all claims to the contrary: societal problems remain wicked problems to design to which design has no 'fixes' (Vermaas and Pesch 2020). We do posit that the engineering systems perspective is an important new development within engineering that takes account of the connected and evolving nature of society, yet it should not be interpreted as offering "socio-technological fixes' to our problems.

A third, related, concern is the recognition that also interventions created with the engineering systems approach will have unintended consequences. Any intervention can have unintended consequences, and engineering systems design is not exempted from that; it will be more useful to anticipate those consequences. For engineering systems design, consequences may occur at both the technical level and the societal level, through direct impact on the systems intervened in, or through knock-on effects on other engineering systems. A response to this concern may be to see engineering systems design as more ongoing processes rather than as individual projects with a beginning and an end date. From the global perspective that comes with engineering systems, this shift in seeing engineering systems design seems obvious, since engineering systems such as the electrical grid and the civil aviation system are systems that are constantly maintained and developed by design interventions. But also from a more local perspective, suggestions are made that design is developing towards a more ongoing effort in which the unintended consequences of interventions are constantly monitored and topic of further design interventions (Dorst 2019).

The sketched approach to the latter concern leads to a question of coordination of design interventions in engineering systems, and is one of the open questions in the engineering systems perspective, to which we now turn.

Open Questions for the Future

The Handbook provides foundational concepts to designing for societal transitions, and it leads to our observation of five larger open questions that need posing and need addressing. In ► Chapter 35, "Engineering Systems Design: A Look to the Future", of the Handbook, we return to these questions and provide our thoughts about possible answers to some.

First, the above-mentioned question of *how to organise the coordination* of design interventions is an open question from the engineering systems perspective. On the local level, the ongoing monitoring and developing of (the local part of) an engineering system can be coordinated with standard management tools. For coordinating design interventions that occur in parallel and successively across the globe, more thinking is needed to arrive at meaningful and efficient coordination.

Second, an engineering systems perspective demands to *think about the future*. Whilst this seems obvious, it comes far from naturally. Why the way we think about the future matters is because it plays a fundamental role both at conscious and unconscious levels in shaping the decisions we take now. A systems approach to the future means anticipation of the future, i.e., the potential impacts of decisions and knock-on effects of interventions in the web of interconnections. As such, the foremost open questions are: How might we train ourselves to think systemically about the future? How might we learn to act systemically for the future? Taking an engineering systems perspective is a through life learning journey.

Third, finding new ways to live within the resource constraints of the planet, creating acceptable futures for the energy and environmental needs of society, will require *system integration*, cumulative change across multiple sectors, including transport, manufacturing, agriculture, and the built environment. Rapid technology development and ensuing implications will occur in the next decades and the developments will need integration and coherent governance structures. This opens challenging questions that potentially erode our well-proven mental models of growth. Is it time to thoroughly re-think or re-cycle the economic growth model? What are the implications for us as scientists, engineers, politicians, educators, citizens?

Fourth, when addressing practitioners or scholars alike, we need to ask ourselves who is the client and who is the designer? Or, who are the clients and who are the designers? For engineers, it might seem strange to ask such questions. Yet, how might we answer such questions for the (re-)design of large sociotechnical systems that the Handbook is about? Society is the client, or, accepting plurality in our current world, societies are the clients. And we all are designers. Each and every one of us has to play that role. How might we raise awareness that *responsibility lies with everyone*? Consequences and implications of our actions originating in the past, taken now, implicate future generations. Hence, linking to the above, we need to train ourselves to lead *from* the future, to become system stewards. This challenges us all, as it impacts deeply on personal levels to change our behaviours.

Fifth, open questions include how we might bring latest research insights together with practice-based implementation. If we want to educate leaders, we have to take a larger point of view, a systems point of view. If we want to empower engineers in positions of authority, we need to change engineers *education* towards a more balanced educational model, throughout the life cycle of a person's career, starting with school and university. Engineering systems design is *through life learning*. This also means creating a skilled workforce, upskilling, re-skilling across work sectors, across work disciplines. We all need new skillsets of how we think and talk about situations, about potential solutions. What perspectives we highlight, regardless of talent, knowledge, time, technological foundations, and investment, we need to create valuable opportunities for collaborations ahead. And in this, one of the main open questions then is: How do we learn and train our ability to connect, and disconnect for that matter, i.e., to master *connectability?*

This Handbook provides a glimpse into the bodies of knowledge in engineering systems design, augmenting retrospective or short-term sensemaking (Weick 1995) with prospective or long-term meaning making (Vorre Hansen and Madsen 2019: 93). The chapters in the Handbook written by experts give many answers in the form of propositions, methods, and tools and provide conjectures as food for thought and calls to action going forward.

In the next section we give an overview of the different chapters in the Handbook. And in ► Chapter 35, "Engineering Systems Design: A Look to the Future", we return in a more explorative manner to the overall challenges our society faces and to the prospects of addressing them by engineering systems design.

Content: The State of the Art of Engineering Systems Design in Five Parts

The Handbook is an authoritative compendium and reference source on Engineering Systems Design written by leading experts in the field. It is written for scholars as well as practitioners interested in transforming society. It is for research- and education-, for industry- and policy leaders. The Handbook provides a comprehensive, cumulative summary of major approaches being used in studies of engineering systems design, the state-of-the-art and findings resulting from the approaches. The Handbook serves both to define the field 'as it is' and provides a point of departure for subsequent work. Each chapter provides a comprehensive review about the specific topic of the chapter and lays the foundation for follow-on work. The breadth of this summary is not indicative of the entire range of possibilities of engineering systems design, esp. at the intersection and interplay between engineering and social sciences, but rather instead, a representative sampling. The information presented is based on state-of-the-art compiled and set in perspective by leading authors across the globe and across scientific disciplines. Wherever possible, the Handbook is illustrated with real or worked examples from contributors who have considerable relevant experience of aspects of engineering systems design processes.

The Handbook of Engineering Systems Design is composed of five parts. The first part starts with the basics of the engineering systems perspective. The second part covers the core characteristics of engineering systems. The third part deals with designing interventions. The fourth part reflects on the developments and leading thoughts to-date, calls to action forward, and introduces a number of cases in the health and transport sectors. The fifth part concludes with a look to the future.

Part I: The Engineering Systems Perspective

PART I *The Engineering Systems Perspective* presents the academic roots of engineering systems design and includes a discussion on the 'Zeitgeist', i.e., sustainable and digital as central topics, and anchors systems thinking and systems-led design as base for how an engineering systems perspective provides solution opportunities for complex societal challenges. This first chapter gives the editors' perspectives on engineering systems design and its societal importance. Maier et al. highlight the opportunities through designing interventions taking a systems perspective and give a synopsis of each chapter in the Handbook. In ▶ Chapter 2, "History of Engineering Systems Design Research and Practice", a review of the historical developments in engineering systems design from antiquity to the present day is given. McMahon notes especially the continual increase in recent years in the sophistication and interconnectedness of engineered artefacts, and development, from the late nineteenth century, of vast networks for energy, communications, and transportation. ▶ Chapter 3, "Design Perspectives, Theories, and Processes for Engineering Systems Design" introduces several well-established design accounts. Isaksson et al. discuss how each approach offers valuable insights that help to address different aspects of complex systems design. In ▶ Chapter 4, "The Evolution of Complex Engineering Systems", the notion of sociotechnical engineering systems evolving over generations of products and policies and of long-life cycles over many decades is described, and tram transportation in the UK and Germany is used as illustration. Eckert and Clarkson explain the evolution of systems, highlighting path dependency, which explains how future designs are restricted by decisions taken in the past, and engineering change, which handles the effects of a change on parts of the system and neighbouring systems. ▶ Chapter 5, "Sustainable Futures from an Engineering Systems Perspective" provides an overview of key sustainability developments in the past, which have laid the foundation for how engineering systems can contribute to a sustainable future through holistic sociotechnical design. McAloone and Hauschild describe core concepts including planetary boundaries and circularity and overall address the question how systems approaches can contribute to sustainability goals. Following sustainability, another major topic is reviewed: ▶ Chapter 6, "Digitalisation of Society". The chapter includes digitisation as mainly referring to implications of digital technologies and digitalisation covering changes in society more widely, including business and governmental organisations. Spath et al., highlight opportunities through Industry 4.0 for industrial sectors such as mechanical engineering or the automotive industry in particular. Concluding Part 1 of the Handbook, ► Chapter 7, "Systems Thinking: Practical Insights on Systems-Led Design in Socio-technical Engineering Systems" describes fundamental concepts of systems thinking and introduces systems-led design. Kaur and Craven point out that systems thinking has gained momentum helping to understand and respond to complex phenomena and illustrate by application to the challenge of tax system design at the Australian Taxation Office.

Part II: Describing Engineering Systems

PART II *Describing Engineering Systems* builds on the Handbook's underlying systems perspective, provides foundational concepts, and moves to describing the core challenges and characteristics of engineering systems, namely, technical and social complexity, multifacetedness of human behaviour, uncertainty and dynamics of long lifecycles, and core properties of engineering systems, sometimes referred to as *ilities* or non-functional requirements. In ► Chapter 8, "Technical and Social Complexity", key drivers of complexity are identified and analysed, including increased interconnectedness amongst systems constituents (network complexity) and multi-level decision-making (multi-agent complexity). Heydari and Herder argue for complexity management instead of complexity reduction and see the introduction of AI into engineering systems playing a significant role in managing complexity and effective governance of such systems. Connecting to complexity management from the human vantage point, ► Chapter 9, "Human Behaviour, Roles, and Processes" focuses on the user, the designer in an interdisciplinary exchange with different stakeholders as experts from different disciplines, such as managers, software systems engineers, mechanical systems engineers, and many more involved in the engineering systems design process. Badke-Schaub and Schaub emphasise that understanding human behaviour is important to conceive why people make certain decisions and why other people do not make decisions at all, and highlight requirements, needs, and safety as guiding principles for the system development process. ► Chapter 10, "Risk, Uncertainty, and Ignorance in Engineering Systems Design" emphasises uncertainty as the third major challenge in understanding and designing engineering systems, together with complexity and human behaviour. Oehmen and Kwakkel provide an overview of managerial practices to address the three levels of increasing uncertainty in engineering systems design: from managing risk, to managing uncertainty, to managing ignorance. The authors of the chapter conclude with a call to action to embrace resilience as a core design objective, both in terms of achieving technical resilience and supporting societal resilience, and thus cohesion through engineering systems design. Concluding Part II of the Handbook, ► Chapter 11, "Properties of Engineering Systems" focuses especially on desired engineering system properties and their relevance to designing effective interventions that ultimately result in sustainable value delivery to society. Rhodes and Ross present the definition of property as an attribute, quality, or characteristic of something, provide an overview of many such properties and highlight four that have been widely recognised in traditional engineering, namely: quality, safety, usability/operability, and maintainability/reliability.

Part III: Designing Engineering Systems Interventions

Part III *Designing Engineering Systems Interventions* describes the process of designing interventions from planning and analysing, to developing and implementing, to evaluating and testing their impact, and covers the tasks related to designing interventions in engineering systems. It operationalises what the previous two parts have laid out in terms of overall goals, context, and the specific challenges that engineering systems pose. The core challenge is that, while engineering systems are highly complex and integrated systems, effectively they are changed through one (or a handful) of their elements and interrelations at a time. While we recognise the potential benefits of centrally 'managed' engineering systems, their de-facto decentralised nature requires us to develop methods allowing us to work on and improve the global performance of engineering systems through mostly localised changes, whilst trying to anticipate the potential ripple effects. In ▶ Chapter 12, "Engineering Systems Design Goals and Stakeholder Needs", we start the (re-)design process with the topics of understanding stakeholder needs and formulating engineering system design goals. McKay et al. introduce three overarching approaches to the design of engineering systems (user-driven design, designer-driven design, and systems engineering) and provide examples of their application to practical design work through three cases at different levels of scale: the design of a surgical device, the design of a knowledge management system, and designing in response to sustainable development goals. From there, ▶ Chapter 13, "Architecting Engineering Systems: Designing Critical Interfaces" logically flows with a discussion on system architecture, understood as the fundamental structure of a system as a focal point where novel designs are discussed, often in terms of integrating new technologies into existing system architectures. Jankovic and Hein emphasise the key aspect of addressing system architecture is identifying, modelling, and managing critical interfaces. The concept of system of system is introduced and examples from aerospace as well as space flight are given. In ▶ Chapter 14, "Data-Driven Preference Modelling in Engineering Systems Design", data-driven approaches for multi-stakeholder decision-making in engineering systems design are discussed, including value-based models, agent-based models, and network-based models for heterogeneous customer preference modelling. Chen et al. provide two case studies on vehicle systems design to highlight the steps of network-based customer preference modelling and to demonstrate its advantages in visualising and modelling the complex interdependencies among different entities in a design ecosystem for data-driven design interventions.

Having focused on system analysis in this part of the Handbook so far, the next chapter now turns to system development, starting with the topic of ▶ Chapter15, "Formulating Engineering Systems Requirements", essential to coordinate purpose-driven activities distributed over several stakeholders. Zimmermann and De Weck focus on requirements from both a receiver's and a provider's perspective and provide an overview of approaches to requirements management from elicitation, analysis, triage, specification as well as verification and validation and of typical forms of documentation and formulation rules. A summary of quantitative requirements analysis methods rounds off the chapter, with emphasis on simulation, isoperformance analysis, analytical target cascading, and solution space optimisation. In ▶ Chapter 16, "Designing for Human Behaviour in a Systemic World" an overview and synthesis of theories and examples of behavioural interventions available to designers is discussed, from fields spanning the natural-, social-, behavioural-, health-, and technical sciences. Maier and Cash review literature from two perspectives 'technology-first', where technology is the primary driver of design, and 'human-first', where it is human behaviour that is the focus and driver and from three main levels of intervention: i) individual or micro-, ii) group or meso- and iii) societal- or macro-level. Perspectives and levels are synthesised via a 'design as connector' lens, bridging insights ranging from engineering to policy. The authors of the chapter propose four main points of guidance, illustrated by examples from health behaviour, sustainable behaviour, and urban planning. ▶ Chapter 17, "Designing for Technical Behaviour" follows, focusing on strategies for technical design of engineering systems, allowing designers to achieve both technical and business objectives. For achieving both functional properties as well as emergent properties, Panchal and Grogan present an overview of design strategies and their respective strengths, limitations, and trade-offs such as complexity vs. robustness, requirements vs. value, modularity vs. performance, and the interactions between social and technical aspects. Strategies include hierarchical decomposition, modularity, design for emergent behaviours such as design for quality, design for changeability, and, more generally, design for X, modelling and simulation, and optimisation-based strategies. When designing for human- and technical behaviour in a systemic world, core concepts such as dynamics and emergence have to be taken into account. ▶ Chapter 18, "Dynamics and Emergence: Case Examples from Literature" discusses the two core and closely linked concepts with the view towards understanding both the trajectories of evolution of systems and correspondingly the patterns of system behaviour, i.e., comprehending emergence in systems through emphasising the dynamics of interactions. To illustrate, Mansouri and Štorga review and summarise the topics of emergence and dynamics through their applications in six case examples conducted by researchers around the world, representing a portfolio of cases studied with multiple theoretical foundations, levels of scope, application domains of engineering systems design, phenomena of emergence, and modelling methods used that detect and identify emergence through dynamics. From a portfolio of examples from literature, ensuing, ▶ Chapter 19, "Designing for Emergent Safety in Engineering Systems" focuses on emergent safety hazards, i.e., hazards emerging from a system without arising from any part of the system alone, but because of interactions between parts. Taylor and Kozine emphasise approaches that consider such hazards as sociotechnical systems, that is, representation of a system by sequential functionally unrelated processes that can in reality influence the performance of each other via sneak paths and other approaches that consider such hazards as cyber-physical systems that focus on the analysis of control loops (feedback, feedforward, positive and negative) and, especially, interrelated loops. The authors conclude the chapter with general guidance for avoiding and eliminating safety hazards when designing engineering systems. Following designing for socio-technical safety, ▶ Chapter 20, "Flexibility and Real Options in Engineering Systems Design" describes flexibility as a core system property, providing systems owners and operators with the ability to respond easily and cost-effectively to future changes and to contribute to improved economic value, sustainability and resilience, by enabling systems to adapt and reconfigure in the face of uncertainty in operations, markets, regulations, and technology. Cardin et al. provide an overview of the development of literature in design for flexibility, design frameworks, methods and procedures to support such design activities in practice, with an emphasis on Real Options Analysis, which focuses on quantifying the value of flexibility in large-scale, irreversible investment projects. Supporting case studies in aerospace, automotive, energy, real estate, transportation, and water management are presented and key future directions for research are given, involving sustainability and resilience, data-driven real options, empirical studies and simulation games, machine learning, digital twin modelling, and 3D virtualisation.

Having gone from system analysis, to system development, the following three chapters move to treating topics of system evaluation. In ▶ Chapter 21, "Engineering Systems in Flux: Designing and Evaluating Interventions in Dynamic Systems", an overview of state of the art on approaches for designing and evaluating interventions in dynamic systems is provided. Bots discusses strengths and weaknesses of a number of design strategies and highlights exploratory modelling and participatory modelling as methods for ex-ante evaluation of interventions in dynamic engineering systems. This leads to the topic area of ▶ Chapter 22, "Engineering Systems Integration, Testing, and Validation" with the focus on multiple testing approaches, including an introduction to parametric cost models, knowledge gradient algorithms, and the sequencing of tests. Valerdi and Sullivan illustrate the support for decision makers for co-ordinating, prioritising, sequencing, and learning through such testing methods with examples taken from the International Space Station and a drone delivery. To come full circle in the intervention design process, ▶ Chapter 23, "Evaluating Engineering Systems Interventions" discusses two types of engineering system interventions, namely, those that change system behaviour and those that change system structure, and moves to discussing the types of measurement that can be applied to evaluating such interventions, contrasting experimental, data-driven, and model-based approaches. Schoonenberg and Farid conclude the chapter with a taxonomy of engineering system models including graphical models, quantitative structural models, and quantitative behavioural models.

Part IV: Reflecting on Engineering Systems Interventions

Part IV *Reflecting on Engineering Systems Interventions* raises awareness for potentially underlying biases, including in the way questions are phrased, design methods are used, and efforts are organised. Chapters in this part raise awareness for research methods supporting engineering systems design, for learnings with examples from megaproject organising, for the potential biases and consequences of choices, i.e. on the way engineering systems designers choose to conceptualise and frame situations, on what methods and tools they may use, and how interventions may be organised and implemented and what impact this may have, on ethics and equity of access, and on the roles and skills of engineering systems designers forward. ▶ Chapter 24, "Research Methods for Supporting Engineering Systems Design" provides an overview of different methodological paradigms in different disciplinary research traditions. Szajnfarber and Broniatowski review quantitative observational research, including inferential statistics and machine learning, qualitative observations research, theory-informed in vivo and quasi-experiments and mathematical representation-informed in-silico experiments. The authors highlight that different types of conclusions may be drawn from these research approaches and research methods, with a specific focus on the ways such research approaches and research methods seek to guarantee validity and a reflection on respective ensuing implications and conclusions that may be drawn. The authors conclude the chapter by emphasising that engineering systems, with their technical and social, cyber, and physical components interacting, are best understood when studied from multiple methodological lenses simultaneously. ▶ Chapter 25, "Transforming Engineering Systems: Learnings from Organising Megaprojects" follows with a reflection on why is it so hard to design, deliver, and yield long-term benefits from megaprojects as interventions in engineering systems? Grounding the work in the project studies literature, Geraldi and Davis discuss four challenges of managing megaprojects: delivering purposeful interventions, integrating complex work under high levels of uncertainty, collaborating with friends and foes, and innovating and learning under high time and budget constraints. Illustrative examples, including the London 2012 Olympics, The Sydney Opera House, and the Berlin Brandenburg Airport are provided.

The following three chapters emphasise the criticality of reflecting on engineering system designers' choices; choices of asking questions, of choosing means, and of organising efforts. ▶ Chapter 26, "Asking Effective Questions: Awareness of Bias in Designerly Thinking" emphasises that asking effective questions allows the curious mind to learn about the environment around them. Formulation of questions is often affected by cognitive biases and preconceptions, in turn influencing decisions and affecting impact. Price and Lloyd conclude with an appellative question on how we might become more responsible and more conscious designers? ▶ Chapter 27, "Choosing Effective Means: Awareness of Bias in the Selection of Methods and Tools" reviews methodological means in engineering system design and the broader design literature and reviews (in-)built biases. Daalhuizen and Hjartarson focus on five aspects: (i) the method user; (ii) method content; (iii) method selection; (iv) acquisition of new methods; and (v) selection aid. To link theory to practice, the chapter reviews how method selection is aided giving an overview of 20 online design toolkits. Then, building on a taxonomy of thinking errors and biases in cognitive science, the chapter identifies relevant biases in choosing methodological means in engineering system design. Having elaborated on engineering systems designers' thinking, on designers' method and tool use, ▶ Chapter 28, "Creating Effective Efforts: Managing Stakeholder Value" reviews stakeholder value management approaches from project management, including project definition, project governance, project delivery, contractual relationships, and project outcome transfer, and reflects on how these approaches might enrich current practices in the design of engineering systems. Romero-Torres and Brunet illustrate the value of projects and respective approaches with reference to standards and practice guides and conclude with a discussion on the influence of stakeholders' biases.

▶ Chapter 29, "Ethics and Equity-Centred Perspectives in Engineering Systems Design" highlights ethics and equity-centred perspectives as critical for the advancement of engineering systems design. Glover and Hendricks-Sturrup summarise varying ethical considerations within the literature, including distributive justice, procedural justice, safety ethics, privacy and trust, autonomy, and sustainability. The authors then discuss the influence of assessing ethical behaviour at the micro-, meso-, and macro-levels of analysis and present five ethical themes in the current engineering systems design literature: integrating ethics and equity-centred perspectives into design, recognising system boundaries, developing augmented system design criteria, managing trade-offs and conflicting values, and educating systems designers. This multilevel approach is illustrated with examples from health. From ethics and equity to ▶ Chapter 30, "Roles and Skills of Engineering Systems Designers", the next chapter describes and illustrates that engineering systems designers must consider not just the artefact but also its associated services, the ecosystem and supply chains necessary for its creation and operation, the communities where it is produced and operated, its relation to government regulations and policy, its impact on the environment, and its long-term influence on social behaviours. Papalambros reviews the roles and skills of engineering systems designers required, emphasising design- and systems thinking, and explores the organisational and social motivations behind this evolution in thinking, how such skills may get acquired, and discusses the implications for individual designers, building the bridge to Part V of the Handbook.

Part V: Futures of Engineering Systems Design

Part V *Futures of Engineering Systems Design*, provides guidance to current and future challenges in engineering systems ways of seeing and designing, highlights opportunities that effective engineering systems design will bring, illustrated with case examples in healthcare and transportation infrastructure, and provides avenues for moving forward, from university education to public policy. This part of the Handbook is opened with ▶ Chapter 31, "Educating Engineering Systems Designers: A Systems Design Competences and Skills Matrix" showing evidenced with literature that there has been a gradual change in emphasis in design education, from technical projects, to systems engineering and more recently, the need to tackle complex sociotechnical engineering systems challenges. Consequently, Moultrie proposes a 'systems design competences and skills' matrix for engineering systems design to help design students and educators consider the boundaries around an individual design brief and to consider how a series of design briefs combine to deliver a balanced programme of design education. The matrix is illustrated through six case examples from university engineering programmes, each of varying levels of complexity. ▶ Chapter 32, "Engineering Systems Interventions in Practice: Cases from Healthcare and Transport" describes four real-world practice examples of engineering systems design from Denmark, two in healthcare and two in transportation infrastructure: Transforming national healthcare by construction of super hospitals: developing deep emergency response using Artificial Intelligence (AI), decarbonising global shipping in a global system transformation, and prototyping future urban transport systems. Thuesen et al. document findings across the cases in five learning points: engineering systems design, firstly, applies a systems perspective to understand the entanglement of different system elements, their connections, boundaries, and causal effects; secondly, evaluates the value of these systems in the light of current performance, state of play, (future) technological possibilities, and user needs to identify complication and societal business cases for interventions; thirdly, organises a lineage of projects and programmes across time and space for systematised experimentation to explore the solutions space and implementation at different levels in the engineering system; fourthly embeds standardisation and flexibility in the system for maintaining value delivery while embracing future needs and opportunities; and finally, carefully navigates the complex and dynamic stakeholder landscapes, manages, and develops the discourse within and around the systems through user and public engagement to ensure benefit realisation of the intervention.

Moving from example cases from industry and public organisations to governance, ▶ Chapter 33, "Public Policy and Engineering Systems Synergy" explores an engineering systems perspective for public policy, emphasising the interplay between technical, social, and societal aspects and discusses regulations as a form of intervention. Meijer et al., focus in particular on a historic overview of how the role of participatory methods has grown over time to capture human complex thinking in a world dominated by mathematical modelling approaches. It positions engineering systems to encompass public policy as an integral part of design, so that the traditional divide as the authors argue between engineering and societal contexts can be bridged.

▶ Chapter 34, "Transitioning to Sustainable Engineering Systems" comes full circle to the beginning of the Handbook and discusses how the industrial exploitation of engineering and technology over recent centuries has impacted on the Earth's ecosystems, ranging from extraction of non-renewable resources to the deleterious effect of many pollutants. The chapter reviews such impacts raising awareness for how human activities have to be seen in connection with the interlinked physical, chemical, biological and human processes that transport and transform materials and energy in complex dynamic ways. McMahon and Krumdieck then outline literature propositions and perspectives on transitioning to sustainable engineering systems, including the use of system modelling methods, engineering approaches to system change to reduce the impact of human activities, ranging from efficiency improvements, sobriety and substitution through addition of functions for improved control of systems to servitisation, to the various approaches of the circular economy, and to introducing transition engineering as a systematic approach to the embedding of sustainability thinking into engineering practice. ► Chapter 35, "Engineering Systems Design: A Look to the Future" addresses the complex issues the world is facing. The Editors, speaking now as authors, are proposing *connectability* as the means to creating meaningful futures in a systemic world.

Cross-References

► Engineering Systems Design: A Look to the Future

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History of Engineering Systems Design Research and Practice

2

Chris McMahon

Contents

Abstract

This chapter reviews developments in engineering systems design from antiquity to the present day, noting especially the continual increase in recent years in the sophistication and interconnectedness of engineered artefacts, and development, from the late nineteenth century, of vast networks for energy, communications, and transportation. Large projects required enormous engineering effort from substantial and often distributed teams, while the networks that developed were "partially designed, partially evolved" with their design and configuration influenced by global actors. These engineering developments led to the need for new tools, methods, and approaches to support engineers in their work, and these are reviewed, beginning with the introduction of drawings – measured plans – and developing through design methods to systems engineering and project management in the latter part of the twentieth century. Concurrently, there was the emergence in the scientific community of the notion of a system,

C. McMahon (✉)
School of Civil, Aerospace and Mechanical Engineering, University of Bristol, Bristol, UK

Department of Civil and Mechanical Engineering, DTU-Technical University of Denmark, Kongens Lyngby, Denmark
e-mail: chris.mcmahon@bristol.ac.uk

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which led to new scientific studies, from systems analysis and cybernetics to network science and soft systems methodology. These various strands have come together at the beginning of the twenty-first century to a multifaceted present state, in which many different lines of research and practice may be brought to bear on the engineering systems design challenges of the century, of complex systems of systems, and their interaction with an increasingly overburdened natural world.

Keywords

Design methods and tools · Engineering systems history · Soft systems · Systems engineering · Systems thinking

Introduction

While one might regard the notion of engineering systems as a recent development, if we consider the ways that important functions in society, such as the supply of water, food, energy, and shelter, are typically fulfilled by artefacts with significant interwoven technological and social complexity (de Weck et al. 2011), then such systems have existed since antiquity. Through history, these will have been amongst the most highly organised and knowledge-intensive aspects of the societies that created them. Consider, for example, the organisation, knowledge, and skills required for the Romans to build the concrete artificial harbour at Caesarea (Brandon et al. 2014) or their network of roads or aqueducts. Or consider the organisation, knowledge, and skills required in the nineteenth century to build continent-wide communication and railway networks, requiring their engineers to design whole systems, not just individual artefacts like locomotives. These posed enormous challenges to their contemporary societies, just as the design, operation, and evolution of the interlinked networks that pervade our lives today are amongst the greatest challenges of our age.

The practice of considering engineering in systems terms is however a more recent one that emerged from the great engineering developments of the end of the nineteenth century and first half of the twentieth century. Examples are the immense networks for communications and the provision of electricity and ever-more complicated engineering hardware, particularly for flight, power generation, and military purposes. It also developed from a more general appearance in the twentieth century of "systems" ideas as a way of viewing the natural and artificial world. From these, "systems thinking" tools and methods were developed, specifically motivated by a systems viewpoint, and "systems engineering" arrived as a discipline. This chapter will explore the interwoven history of engineering, of engineering tools and methods and disciplines, and of wider systems ideas that is behind today's understanding of engineering systems design.

This chapter will start with a very broad overview of those engineering developments from antiquity in which, in retrospect, the concept of systems may be seen, before moving onto the emergence, in the seventeenth and eighteenth centuries, of artefacts of significant engineering sophistication, especially, for example, military fortifications and naval vessels (McGee 1999). The exponential growth of engineered networks (railways, electrical, telegraphy) in the nineteenth century (Hughes 1993), together with the appearance of very large projects to deliver highly complex artefacts (supersonic aircraft, the Manhattan and Polaris projects, the Apollo moon landings), will then be presented as a driving force in the emergence of systems ideas in engineering.

The following section will then explore how, over a similar timescale, tools and methods emerged to support the activities of engineering design, especially, for example, in the emergence of formal approaches to engineering drawing in naval architecture in the seventeenth and eighteenth centuries, to allow “the application of mathematical and physical theory in design, long before the modern era” (McGee 1999). It will be argued that similar pressures led in the twentieth century to developments such as computer-aided design and manufacture and the emergence of systems engineering “coordinating the functions of constituent components and subsystems and overseeing the engineering efforts of those who developed them” (Sato 2005). From this background, the key ideas of systems engineering will be presented, including such issues as systems architecture, modelling and simulation, systems analysis, and so on.

Concurrently with the developments in engineering, developments in the sciences were leading to the emergence in the scientific community of the notion of a system as a “generalisation of ideas about organisms which were developed within biology in the first half of the twentieth century” (Checkland 1999). The concept of a system became useful as an explanatory device in a variety of scientific endeavours. In the next section, the origins of a number of core systems ideas – such as adaptive wholes, emergent properties, layered structures, and processes of communication and of control – will be presented, together with a discussion of such issues as cybernetics, complexity, and network science and the distinction between hard systems and soft systems.

By the latter part of the twentieth century, systems engineering approaches to the design and delivery of “one-time, large projects with a definite start and end, where a new system is to be designed and created to meet customer needs” (Sato 2005), were mature and well-described. They were, however, still the subject of significant research, as was the question of how we understand systems that are “partially designed, partially evolved” (e.g., De Weck et al. 2011). In particular, we will consider complex “systems of systems” in today’s interconnected networks in which engineering challenges are intimately mixed with social, institutional, political, and environmental issues and in which design of policy and intervention can be as important as design of the physical elements of the system. In the final sections of the chapter, these developments will be broadly described, together with the rapidly developing use of systems approaches to understand the behaviour of designed artefacts embedded in our cultural and socio-economic systems and their interaction with the sociopolitical and natural world.

Origins

De Weck et al. call engineering systems “the systems that fulfil important functions in society [. . .] characterized by high levels of interwoven technological and social complexity” (de Weck et al. 2011). Arguably, the approaches that the Romans used for transportation and water supply conform to that definition. Consider the social organisation necessary to gather the materials needed to construct many kilometres of roads or aqueducts (Davies 1998) or the technical understanding and energy needed to produce the vast quantities of concrete, able to set underwater, used for the artificial harbour at Caesarea in the Eastern Mediterranean (Oleson 1988). There was evident “interwoven technological and social complexity” needed for the provision of transportation and water, although of course clearly distinguished from what pertains today by the scale of the interactions and the numbers of actors and technologies involved.

After the fall of the Roman empire, it was some centuries before engineering in Europe re-emerged at a similar scale, first perhaps in the great palaces and cathedrals of the medieval age and then by the seventeenth and eighteenth centuries in naval shipbuilding and military fortifications that were amongst the most complicated activities undertaken at the time. These required considerable investment in materials, construction facilities, and trained labour and coordination of their interaction. A significant part of seventeenth century Copenhagen, for example, was devoted to the construction of naval vessels, and the oak tree, source of timber for ships, was of very great socio-technical importance at the time (Eliasson and Nilsson 2002).

Ships were also a key technology for the transportation networks of the time. The seventeenth and eighteenth centuries saw considerable growth in shipping routes and networks and in ports for the loading and unloading of ships. By the end of the eighteenth century, London had many kilometres of wharves such that by the early nineteenth century dedicated docks had to be built. It was in this century that what became the modern engineered networks emerged, with metaled roads, country- and continent-wide railway networks, sewers and water supply, and then telegraph and electrical networks. The century also saw the increasing linking together of these – telegraph networks being built alongside railways and being used to communicate between signalling staff and then electrical power being used for rail vehicles and trams. The social-technical effort required to achieve all of these – the banking systems, construction and manufacturing enterprises, schools, and then research and training institutions – was considerable (Hughes 1993). The century also saw the founding of institutions of engineering education and the beginning of a number of engineering professional groups. The main technical evolution of the core networked systems was undertaken by many groups, often competing on an international basis. Nevertheless, engineering very much involved “a lot of material connected together by a little knowledge”, and significant technical leaps were still very often made by individuals (Hughes 1993; Little 2000).

In the twentieth century, the effort involved in the development of engineering artefacts expanded exponentially, especially during and after the Second

World War. In 1940, the engineering effort required for development of a fighter aircraft was 17,000 hours. By 1955 it was 1.4 million hours (Johnson 1997). The Manhattan project to develop the atomic bomb and then projects to develop Polaris missiles and nuclear submarines, large radar systems, civilian nuclear reactors, and the Apollo spacecraft required the coordination of very large, distributed teams and were often carried out under conditions of considerable initial uncertainty. By the end of the century, the design of single artefacts with enormous numbers of interconnected parts – ten million transistors in a single integrated circuit, many million discrete parts in a commercial aircraft – was routine.

These were the one-time, large projects with a definite start and end described by Sato (2005). It is possible to identify the individual actors that come together to design and build an aircraft or an integrated circuit. If, however, we examine how our engineering networks have evolved, this becomes an impossible task. Long distance telephone, radio, television, the Internet, mobile telephony, and satellite communications were added to the relatively simple telecommunications networks of the end of the nineteenth century and rapidly became ubiquitous. There was also an explosion of growth in electrical and transportation networks, reaching billions of consumers by the end of the twentieth century. These networks were, and are, "partially designed, partially evolved" (de Weck et al. 2011), built on foundational rules and principles – standards and protocols – within the framework of which diverse actors are free to propose developments.

De Weck et al. describe this progression over the past century or so as developing from the "epoch of artefacts and inventions" through the "epoch of complex systems" in the middle of the last century to the "epoch of engineered systems" today. We can also summarise these developments in terms of an increase in numbers in multiple dimensions:

- The number of different physical principles exploited by the technologies embedded in our artefacts – from elastic resistance of materials through combustion and electron flows to radio waves.
- The number of specialists needed in those physical principles – from civil and mechanical to electrical and communications engineers.
- The number of parts involved in artefacts from simple boats and buildings to complicated aircraft and integrated circuits; the number of nodes and connections in networks – from early electrical networks powering a few hundred light bulbs to the Internet with billions of nodes.
- The number of people and organisations involved in the design and manufacture of the artificial world.
- The length of time over which they interact.

These numbers, and the interactions that they lead to – with each other and with the natural world – mean that we have a great need of approaches to help us deal with the consequent challenging complexity.

Approaches to Support the Engineer

Alongside the development and application of engineering technologies have come the development and application of approaches – such as tools, methods, systems of organisation – to assist engineers and other actors in the design and implementation of the technologies. Marcus Vitruvius Pollio, commonly known as Vitruvius, documented Roman practices in architecture and construction in the first century BC in his multivolume work entitled *De architectura* (McEwen 2003), but it was with the complicated military artefacts of the renaissance – especially fortifications and naval vessels – that some of our modern engineering tools began to emerge. From those beginnings, the last two centuries have seen continual development, often highly influenced by the cultural context in which it has taken place.

In (McGee 1999), David McGee explores the development of the use of formal engineering drawings – "measured plans" in naval architecture in seventeenth century Britain. He notes that at that time British naval dockyards were the largest industrial organisation in the world and remained so throughout the industrial revolution that followed. McGee builds on J. Christopher Jones's argument that the development of design based on drawings during the Renaissance marked a shift from "craftsmanship to draftsmanship" because of "the advantages provided by drawings with respect to both construction and innovation" (McGee 1999). McGee notes that Jones argued that drawing permitted tentative design decisions to be stored allowing the design of more complex artefacts by enabling designers to deal with an otherwise "unmanageable, and unimaginable, degree of complexity" (Jones 1992, quoted by McGee). He argues that such measured plans were used predominantly as an architectural tool and because of the need to control production costs. The use of measured plans was central to an architectural tradition to control construction, while for the exploration of ideas and mechanical arrangements, designers still used "rough, single-view, back-of-the-envelope style sketches". McGee also argues that "neither levels of complexity nor different kinds of constraints drive the adoption and development of new design methods, but rather different levels of cost do". This in turn "yields a narrative in which similar human beings struggle with different contexts of risk". McGee notes also that early hopes to enlist a higher level of scientific contribution to the design process were relatively unsuccessful.

Over the following centuries, measured plans – engineering drawings – became firmly embedded in engineering practice. The formal basis of descriptive geometry was established by Gaspard Monge at the beginning of the nineteenth century (Monge 1811), and, during that century, detail drawings came to be used, together with tolerance dimensions, as a means of achieving interchangeability of parts, especially in arms manufacture. During the century, they also became a key driver of the US system of manufacturing, described by Brown (2000) as an example of the importance of social institutions in shaping technical activities. Comparing US and British engineering practice from the mid-nineteenth century, Brown relates how American engineers "devoted themselves to standardising design elements and rationalising production", "subdividing work through working drawings and other industrial engineering measures", so driving down the price of their products. British engineers, by contrast, often pursued a different course, focusing on design creativity and the generation of customised products, realised through the strong craft skills of their production workers (Brown 2000) (although it should be noted that British engineers were early users of mass production through Brunel's pioneering system for the production of rigging blocks for the Royal Navy installed at Portsmouth in 1805 (Cooper 1984)).

At this time, standardisation also emerged as a very important issue in the development of networks. In the early days of railway operation, different track gauges were often used by different companies. Interoperability soon made it necessary for national and then international standards to be adopted, not only for the separation of the tracks but also for the loading gauge limiting vehicle sizes (Puffert 2009). The same process would be seen in the development of electrical power with initial competition between AC and DC systems and many different voltages and frequencies used in electrical power systems. In telegraphy, many protocols (and physical arrangements) for message transmission were used before development was allowed to thrive by engineers settling on standard voltages and systems such as Morse code becoming widely used (although differences in practice between the USA, British Empire, and continental Europe persisted for many years). By today, standardisation – whether by regulation or de facto choice of the market – has developed as an underpinning foundation of our digital age (Russell 2014).

Social and political institutions were again very important in the development of electrical power networks, as described by Hughes in his celebrated work (1993). Hughes emphasises that a systems lens should be used to consider the development of these networks and describes the profound influence of political and social factors in such systems by comparing developments in the USA, UK, France, and Germany. For example, the initial legal framework for development established in the UK became a significant constraint on progress. Hughes also provides great insight into the characteristics of the processes of invention and development that pertained at the time, including the interplay between inventors and businessmen and the development of research and manufacturing capabilities. He describes technical progress using the military metaphor of "reverse salients", where, having made progress on other fronts, inventors, engineers, and scientists concentrate their efforts on the critical, difficult problems that stand in the way of development. He notes that development of the technologies was inextricably linked with the development of "massive, extensive, vertically integrated production systems", bringing together finance, production, and operations. Once such systems were established, and the technical knowledge had matured, the technology acquired a "technological momentum" of its own (Hughes, op cit. and Little, op cit.), but the social, institutional, and political continued to have enormous significance in determining the direction of engineering systems development and in guiding the design of policy and regulation.

De Weck et al. describe the end of the nineteenth century and beginning of the twentieth as the epoch of artefacts and inventors, but it was also the time at which business-based research and development laboratories began to be established (de Weck et al. op cit). Edison's establishment of his research lab at Menlo Park in

1876 was one of his major innovations, and Thomson used his model room at the Thomson-Houston company. However, it was the early years of the twentieth century that development really took off, with the establishment of research labs in General Electric, AT&T, and Eastman Kodak, and a profound expansion in scientific research at US universities (Carlson 2013). Following the First World War, the number of research labs grew markedly as companies tried to manage the risks involved in new developments – individual inventors were seen as too unpredictable – and, by 1940, 2000 firms employed over 7000 people in such departments. In part they tackled the critical "reverse salient" challenges that Hughes has described – leading, for example, to the development of feedback control and the transistor by Bell Labs (formed from the 1925 merger of AT&T R&D and Western Electric) – but they also provided important scientific support services to firms. Carlson notes, however, that despite large investment in such R&D labs, blockbuster innovations such as the integrated circuit and personal computer came from small start-up companies, although these were often dependent on military funding and on the large labs for information and personnel.

We have noted in the previous section that by the middle of the twentieth century, and especially during and after the Second World War, engineering development often required the coordination of large, interdisciplinary teams, sometimes working at the very limits of scientific and engineering knowledge. As noted by Johnson, "technological systems had grown too complex for traditional methods of management and development. Existing organisations could not easily assimilate and integrate technologies such as nuclear weapons, radar, and rocket propulsion" (Johnson 1997). Johnson notes that the response was again very influenced by social and cultural factors, in this case dependent on the communities from which the new approaches emerged. Mathematicians developed the new approaches of applied mathematics in *operations research*, and management specialists developed the techniques and discipline of *project management*, while engineers, explicitly using the term "systems", developed *systems engineering*. In Johnson's words, "scientists used their mathematical prowess to analyse current or future operational systems. They did not build these systems; consequently their perception of the problem was *analytical*. By contrast, engineers designed and developed systems to specifications determined by others. Engineers in industry saw systems engineering as a systematic design *process*, consistent with their daily involvement with large projects. Managers made decisions about whether to build systems and controlled their development and use. They organised new communication and control *procedures* around the technical system. Functional hierarchies gave way to more flexible 'team' and 'matrix' forms organised around the end product", and later "the military and the aerospace industry found [these approaches] useful [and] they became the most influential and practical applications of "the systems approach", the core of much of the American R&D system of the 1960s".

From these early beginnings, systems engineering has developed in a number of directions. In 1946 the US Air Force established a nonprofit think tank called the Rand Corporation in the Douglas Aircraft Company. In 1948 it was spun out as an independent corporation. It was highly influential in the development of systems approaches, especially systems analysis, a set of techniques that became core to systems engineering and have been developed through the structured analysis methods of the 1980s to today's modelling languages and model-based system engineering (MBSE) approaches (Dickerson and Mavris 2013). However, by the 1980s, it was recognised that systems engineering did not give sufficient attention to the up-front part of the process and that this was a source of failure in the design and development of many systems. What was missing was a focus on the overall architecture of the system, the coordination of the design across architectural boundaries, and the translation of architectures into modules and organisational structures. This led to interest in systems architecture, a key aspect of design planning and negotiation, drawing on research in software architecture that was also emerging as a significant area of inquiry at that time (Grinter 1999).

At the end of the previous section, it was suggested that engineers needed approaches that would help them deal with the increasing complexity of the engineered world. It is clear that many of the developments that have taken place have been to help deal with complexity, whether, for example, in terms of the number of parts and their interactions or in terms of the number of disciplines and actors involved in engineering processes. But it is also clear that we need to look more closely at the drivers of the development of such approaches and the constraints surrounding the development. The need to manage cost and risk – commercial and technical – has been an important consideration through the centuries, as has the social, political, and cultural environment in which developments have taken place. It is also clear that we cannot isolate the development of engineering systems from the more general systems developments – financial, political, industrial, and cultural – that have taken place in our societies.

In many ways the development of systems engineering approaches in the second half of the last century mirrored interest in the development of approaches to support engineering design more widely, with their emphasis, inter alia, on process (Wynn and Clarkson 2018; Piccolo et al. 2019), on architecture (Jiao et al. 2007), on modelling (Andreasen 1994), and on organisation and management of the actors involved (Badke-Schaub and Frankenberger 1999). During this period, a great deal of interaction has developed between the researchers and practitioners in the two communities and between them and other communities, for example, in mathematics and in the management and life sciences. In the next section, we will consider developments in systems thinking more generally and the application of systems design ideas in domains beyond engineering.

The Wider Development of Systems Thinking

Over the period in which the notion of systems has come to dominate the way we view engineering, systems thinking has been more and more influential in the way that many aspects of the world are viewed. As noted in the Introduction, Checkland (1999) considers that systems ideas emerged as a "generalisation of ideas about organisms which were developed within biology in the first half of the twentieth century". He attributes the emergence of the systems movement to organismic biologists and to the notion that "ideas about organisms could be extended to complex wholes of any kind". In other words, the concept of a system became useful as a general explanatory device for some sorts of entities.

In (Checkland 1999), Checkland is discussing the role of systems thinking in management information systems. His advice is relevant to the design of engineered systems more generally. He makes a number of cautionary points, stressing that that general systems theory cannot necessarily immediately help in the design of systems – there is no simple link – but that systems thinking is very relevant and can illuminate problems. Part of the issue, he says, is language: "there are great difficulties in an ill-formed and conceptually confused field like *management* ... which stem from the fact that there is no language available for serious discussion which is separate from everyday language [...] terms are fuzzy as a result of their unreflective use in everyday chat" (Checkland 1999, p. 46). This is surely an issue that we see concerning the use of language in design and engineering systems more generally. Checkland notes that we talk casually in many domains about so-called systems "which in real life only occasionally and partially actually meet the requirement of the notion 'system' [...] an abstract concept of a [...] complex whole entity of a particular kind" (Checkland 1999, p. 46) (although Checkland does recognise that there are clear "designed physical systems" that engineers design and construct).

Having noted these caveats about the use of language and direct relevance of systems theory to engineering, let us return to the scientific origins. As noted, organismic biologists focused on the organism as a unit of analysis in biology. This was driven by the issue of vitalism in living things, which were clearly more than the sum of their parts. Holistic thinking in biology led, for example, to the development of ideas about metabolism and self-reproduction. The systems movement more generally was founded by Ludwig von Bertalanffy, one of the organismic biologists, who argued, starting in the 1940s, that these "systems" ideas about organisms could be extended to complex wholes of any kind, emphasising holism over reductionism, organism over mechanism (Checkland 1999; Von Bertalanffy 1969). In 1954, a *Society for the Advancement of General Systems Theory* was proposed under the initiative of von Bertalanffy together with colleagues from physiology, economics, mathematics, and the behavioural sciences. It was established in 1955 as the Society for General Systems Research (now the International Society for the Systems Sciences (https://www.myisss.org/)).

Checkland emphasises that it was systems thinking that is useful, rather than systems theory per se, suggesting that "systems thinking has emerged as a meta-discipline and as a meta-language which can be used to talk about the subject matter of many fields". The role of systems thinking as a meta-subject is seen, for example, in the incorporation of cybernetics – the use of communication and feedback systems in the general (meta-level) science of "communication and control in man and machine" introduced in 1948 by Wiener – as a subset of systems thinking (Wiener 1948).

At this point, it is perhaps worth summarising Checkland's proposal of the key ideas of systems thinking, which are:

- The central idea is that of an entity which can adapt and survive in a changing environment – the *adaptive whole* (and, as an aside, we can perhaps see immediately that this is challenging in engineering; a large passenger aircraft, e.g., although extremely complicated, does not meet this notion of an adaptive whole).
- The entity must have properties as a single entity – *emergent properties* – that are more than the sum of the parts.
- Wholes having emergent properties may have smaller wholes with their own emergent properties – there is a *layered structure* (Checkland uses the example of a university having emergent properties and in turn comprising departments with their own emergent properties).
- If entities are to survive, they must have ways of finding out about and responding to their environments – they must have processes of *communication* and *control*.

Checkland notes the success of systems ideas in interpreting the natural world and in designed entities, especially when there could be carefully designed objectives, but he remarks also about the struggle that there was initially when trying to apply systems concepts in human affairs, in part because of the difficulty in defining objectives precisely. But this was often what made the application domain problematic in the first place! This was addressed by introducing the concepts of *purposeful action* and modelling systems, based on a declared worldview, to help structure the problem under study. Such an approach became known as the *soft systems methodology* (SSM) to distinguish it from the hard systems of systems engineering, and which Checkland describes as "learning systems, a system of enquiry, one which happens to make use of models of activity systems". Worldview, problem structuring, purposeful action, and system modelling are today core approaches in systems thinking (Blockley and Godfrey 2017).

Emergence is a general term in systems but applied particularly during the process of self-organisation in complex systems, and, in this regard, it is a key concept in the study of organisational complexity. Goldstein (1999) describes emergent phenomena in complex systems as "neither predictable from, deducible from, nor reducible to the parts alone", noting that "conceptual constructs resembling emergence can be found in western thought since the time of the ancient Greeks"; he traces development of the term from its use in the nineteenth century to describe results of certain chemical reactions and then in the 1920s to form the backbone of emergent evolutionism. He also notes that its current use in complexity theory has its roots in the study of dynamics of systems in the physical sciences and mathematics going back to the Second World War. Emergence requires systems with at least the characteristics of non-linearity, self-organisation, beyond-equilibrium behaviour (e.g., amplification of random events in far-from-equilibrium conditions), and attractors (e.g., limit states and fixed points) which drive behaviour. Goldstein describes this notion of emergence as being important in a number of systems domains (and ubiquitous in organisations), including complex adaptive systems theory, non-linear dynamical systems, far-from equilibrium thermodynamics, and synergetics (Buckminster Fuller 1975) (related to non-equilibrium thermodynamics and exploring self-organisation of patterns and structures in open systems).

An important driver behind the search for problem-structuring methods is the messiness of many complex problems, especially where social aspects are significant. There is a fundamental indeterminacy in such problems, and all but the most trivial issues may fall into this class. Rittel described these as “wicked problems”, a “class of social system problems which are ill-formulated, where information is confusing, where there are many clients and decision-makers with conflicting values, and where the ramifications in the whole system are thoroughly confusing” (Churchman 1967). Wicked problems are often symptoms of other, higher-level problems and have no definitive formulation, although every formulation attempted corresponds to a solution, which can be only good or bad, although there can be no definitive test of this (Buchanan 1992). However, while the term “wicked” is often used in design and systems thinking, in Buchanan’s view, it is a description of the social reality of such approaches rather than the basis of a well-founded theory of design.

In the world of complex, indeterminant, wicked problems, the search has been for “sense-making” devices that can help in explaining and guiding courses of action. Blockley and Godfrey, in their book on systems approaches for rethinking infrastructure (2017), list many of the techniques that emerged in the second half of the twentieth century including the Analytic Hierarchy Process, balanced scorecard, causal loop diagrams and modelling, system dynamics, root definition (CATWOE), stakeholder analysis, SWOT analysis, use case analysis, N2 mapping, mind maps, PESTLE (political, economic, social, technological, legal, and environmental) analysis, and others. They note that a particularly useful framework for such sense-making is Cynefin, devised by Snowden at IBM in 1999, in which decision-making contexts were divided into five categories: simple, complicated, complex, chaotic, and disordered. Blockley and Godfrey suggest that complex corresponds to wicked and/or messy and involves high interconnectivities and highly emergent uncertainties. Complicated contexts are also highly interconnected but well-understood at different levels, while simple contexts, which they call “tame”, are linear, manageable, and controllable. They group chaotic and disordered, using the descriptive term “utter confusion”.

A particularly important approach to the understanding of the dynamic behaviour of systems is system dynamic modelling, originally devised in the 1950s at MIT by Forrester (2007) and which considers dynamic systems in terms of “stocks” (quantities measured at a particular point and time), “flows” (measured over a period of time and analogous to rates of change), “sources” and “sinks” from which flows originate and through which they exit, and cause-and-effect feedback loops, also known as “causal loops”. Forrester’s research team implemented his ideas in executable computer models that were initially applied to management and then urban planning issues but perhaps had their most celebrated application in the Club of Rome’s study of the demands being placed on the world’s carrying capacity, which resulted in the book *Limits to Growth*, published in 1972 (Meadows et al. 1972).

A system dynamics model is an example of a network of nodes (in this case, stocks, sources, and sinks) joined by links or edges (flows). We have seen that in technology and society, networks may be found everywhere – for electricity and communications and for transportation, between people and organisations, and so on. In recent years, the explosion of growth in communications networks, especially the Internet and World Wide Web (WWW), has sparked great interest in network science. This discipline studies the characteristics of such networks under different configurations, building on earlier work, for example, in graph theory and sociograms. Through such study we might understand, for example, what might make the WWW robust or susceptible to attack or how viruses might spread in human populations or amongst computers. Barabási (2002) explains how, for many years, networks were viewed as being random in their interconnections. However, he and colleagues at the University of Notre Dame, studying the topology of part of the World Wide Web, came up with the notion that there are networks in which some nodes (called "hubs") have many more connections than others and that the number of links connecting nodes was described by a power-law. This configuration, which came to be called "scale-free networks", may be seen in a number of other networks, including citation networks, social networks, air transportation route patterns, and so on. While the merits of the scale-free model are the subject of debate, it and related work led to a blossoming of studies on network characteristics in recent years. These include such topics as dynamic network analysis, centrality measures (the relative importance of nodes and edges in a network), and pandemic analysis. Perhaps the most widely used result of such studies is the PageRank mechanism used by Google to rank web pages in their search engine results (Page et al. 1999).

To the Present Day

So, in summary, what can we say about engineering systems design, research, and practice at this point early in the twenty-first century? We must first acknowledge Checkland's caveat regarding the term "system" in everyday usage. There is an enormous variety of applications and potential interpretations of the term, and it is therefore perhaps not surprising that there are multiple threads running through the descriptions of the previous sections. Ask any engineer and he or she will most likely give a good definition of a system and examples of where we can see systems in engineering. Ask about the design approaches that these systems require or whether the examples are complicated or complex, and we might have a debate that lasts all day! Nevertheless, it is possible to identify a number of clear threads running through the historical development that has been described.

The first thread is that engineers develop approaches, tools, and methods for a variety of reasons. They seek help in dealing with complexity and intricacy. They seek help with model building and communication. They use them to predict performance and to allow design to take account of many facets (the "ilities" (de Weck et al. 2011) reliability, manufacturability, maintainability, sustainability, and so on). They allow science to be applied and, especially, to assist in the control of cost and risk. For many of these applications, taking a systems view and using the tools of systems science are especially important in view of the scale, intricacy, and interconnectedness of today's artefacts, whether we explicitly use the term "system" or not.

The second thread is that the particular discipline of systems engineering arose in the middle of the twentieth century, to deal with the complicated, multi-technology artefacts of that time. It grew alongside project engineering and operations research and has identifiable professional groups (e.g., the International Council of Systems Engineering, INCOSE); a mature set of techniques, many embedded in standards (especially concerning systems engineering processes (ISO/IEC 15288)); and an academic infrastructure of courses, departments, and research literature. But although systems engineering practices are applied in many branches of engineering, they are most firmly embedded in aerospace, computing, and defence. Voices in the systems engineering community recognise that systems ideas are applied widely in engineering without the formal term "systems engineering" necessarily being used and even that systems engineering has somewhat of an identity crisis (Emes et al. 2005).

The third thread is that systems ideas and systems thinking developed strongly in the last century, with applications across a range of disciplines and with multiple facets – systems analysis, sense-making and problem-structuring tools and methods, systems dynamics, cybernetics, network science, and more. With origins in the biological sciences, the approaches found a natural application in engineering but also growing applications in business, organisation, and social contexts, which became classed by some as "soft systems", to distinguish from the "hard systems" of engineering. Recognising that engineered systems are produced and operated by human actors, this distinction is perhaps seen less strongly today. Systems approaches are becoming embedded in many aspects of human endeavours, from project, program, and portfolio management (Oehmen et al. 2015) to infrastructure provision (Blockley and Godfrey 2017) to healthcare (Clarkson 2018).

What was the focus of the engineering design research community at that time? At the beginning of the twenty-first century, Andreasen, reflecting on the International Conferences on Engineering Design (ICED), identified four key themes (Andreasen 2001) which have clear parallels with those that we have met in the systems community. The first was a large body of work seeking to explore what constituted design science: what was the scientific basis for the subject and what were the appropriate research methodologies to be used in its study? The second reflected a development from a concentration on mechanical design, especially machine design, to a wider emphasis on product development. There was in particular a developing interest in "design for X" (DfX), where "X" described life cycle properties of the designed artefact that included especially manufacturability and assemblability but also issues related to environmental performance and to design for the whole life cycle. The X here corresponds largely with the "ilities" that we have met. This group also contained papers on teamwork, on the human aspects of design – including collaboration and creativity. The third large group of papers reflected the strong interest at the time in computer-aided design (CAD) but also showed developing emphasis on wider application of information technologies in many aspects of design from automated synthesis to information and knowledge management and many aspects of modelling. Andreasen named a fourth and final body of work “delimitations of ICED”, describing the papers published in this group as broadening out from the engineering focus to a wider interest in innovation more generally. The emphasis on product development reflected very strongly the competitive industrial culture of the time. Design for X – design for manufacture in particular – was perhaps a response to the rapidly escalating labour costs of the 1970s and the prowess that the Japanese had shown in manufacturing productivity but also to the increasing awareness of environmental issues. The emphasis on information technology was a natural product of the rapidly developing computing technologies and in particular the transition to CAD in industry which was taking place very strongly at the time.

Which brings us to the present day and to the term “engineering systems” that has been used to describe the epoch in which the network technologies of the twentieth century – including communications, energy, and transportation – are increasingly integrated and interdependent but also ever-changing as more and more actors add more and more elements to the networks. Any part of any network will have been designed, but there has not necessarily been any design of the networks as a whole, only of the rules and principles on which they operate (or, at the very least, design has been distributed amongst many actors). They are, as noted, partially designed, partially evolved, and furthermore are often “systems of systems”. These are multiple systems that interact but that can and do operate independently of each other (Maier 1998, quoted by de Weck). Electrical and communication systems are classic examples of such systems, but global manufacturing systems and the associated logistics and supply chains are further fine examples (Myerson 2012).

In addition to strong engineering development such as growing capability in modelling and simulation (e.g., Fujimoto et al. 2017), the twenty-first century has also seen a growing emphasis on social and socio-technical aspects of systems (see, e.g., (Kroes et al. 2006) and (De Bruijn and Herder 2009)), in which human agents and social institutions are considered as integral parts of systems. A socio-technical systems approach has been applied to the design of engineered systems such as infrastructure and transportation systems (Ottens et al. 2006), while more widely it has been applied to innovation studies by considering sectors (e.g., regional, groups of firms) in systems terms (Geels 2004). Issues that have been studied include complex systems governance (Jaradat 2015), the achievement of social value (Browning and Honour 2008), and the philosophical underpinnings of the topic (Bauer and Herder 2009). In addition, new academic and professional groupings have emerged with interest in engineering systems design and research, including the Council of Engineering Systems Universities (CESUN, cesun.org), established in 2004 by universities offering educational and research programs in engineering systems, reflecting the developing importance of engineering systems research and teaching in universities around the world.

In the present day, it is also clear that the scale of the complex, interlinked engineered networks that support our current lifestyles is challenging for other reasons: the rates at which we extract materials from natural sources and the rates at which we cast waste materials into global sinks – whether plastics, CO_2, oxides of nitrogen, or other pollutants – are widely believed to be beyond the capacity of our planet to support (Steffen et al. 2015). Measured behaviours are showing good agreement with the system dynamics models of the Club of Rome (Bardi 2011). Achieving a sustainable existence for more than 7 billion inhabitants is arguably the most complex, wicked problem that we have faced. We can design approaches which we hope will be less damaging, but the test of these is likely to be what happens as we try to scale up their adoption – how will they interact with other artefacts, what will the political and social consequences be, and what will be their impacts on the natural world? These are all clearly systems issues and merit a strongly systems-oriented approach in tackling them. Although Williams et al. report that systemic ideas are not yet mainstream in management science literature, the core systems ideas of interconnections, feedbacks, adaptive capacity, emergence, and self-organisation figure strongly in systems thinking for sustainability research (Williams et al. 2017). Geels (2002) suggests that a similar effort to that devoted to the emergence of large technical systems, as described by Hughes and others, will need to be devoted to the characteristics and processes of transitioning from our present technical systems to new less environmentally damaging ones.

In these circumstances, it is very important to realise that, in the context of engineering systems design, especially of complex interlinked networks, designing happens most likely never from scratch: new design work will add to, modify, or partially replace elements – technical and non-technical – of existing systems, and must be done with all the past work on those systems in the background. Effectively we are designing interventions, and such interventions must be based on an understanding of the political and social context as well as the technical. In this regard, there are many possibilities for the way such interventions can be achieved – by new technologies, certainly, but also by new or modified standards and regulations, by political and social action, and by the creation of new or adaptation of existing societal institutions. Any change that is made will also potentially impact all of the other systems that interact with the system in which the intervention is made.

Conclusions

From antiquity, many aspects of the engineered world have been systems, but since the end of the nineteenth century, the sophistication of major artefacts, and the number, scale, and interconnectedness of the networks that support human activity, has led to the need for new approaches to the design and operation of the artificial world. These new approaches have arisen from the demands of the sheer complexity of engineering but in particular from the need to control cost and risk and to enable the efforts of an enormous number of stakeholders to be brought to bear. The new approaches have been developed in different social and political contexts, in turn comprising systems of finance, political organisation, and the like. These contexts have had a large influence on the emergence of engineering systems design research and practice.

In the twentieth century, a specific discipline of "systems engineering" emerged, focused on the design and implementation of technological systems "too complex for traditional methods of management and development". In parallel with this development was the growth of systems thinking in a variety of domains, new systems sciences, and new understandings and research movements in design. The end of the twentieth century saw a veritable melting pot of ideas and movements, all influencing and cross-fertilising each other. Engineering systems now encompasses the realisation of technologically sophisticated artefacts such as aircraft or computers and their embedding in complex operational socio-technical systems involving huge infrastructure and enabled by ubiquitous information technology. Moreover, it encompasses the realisation of the highly interconnected networks of energy, transportation, and communications that are partially designed, partially evolved, while taking intense cognisance of the interactions between the engineered world, social and political systems, and the natural world. Engineering systems design approaches have, in this context, increasingly emphasised social and socio-technical issues and the creation of value.

The success of engineering systems design approaches may be seen all around us, in the remarkable performance of the artefacts that have been created. And yet there is increasing disquiet amongst some observers. These systems depend on finite resources, and their operation threatens the stability of the climate and the ability of land and water resources to cope. It has been suggested that increasing systems complexity comes at a potential cost in terms of resilience and diminishing returns (Tainter 1988). Understanding what should be done to try to address these issues demands a deep understanding of the interaction between engineering systems, human systems and behaviours, and natural systems and may be the greatest challenge yet for engineering systems design research and practice.

Cross-References

- ▶ Design Perspectives, Theories, and Processes for Engineering Systems Design
- ▶ Educating Engineering Systems Designers: A Systems Design Competences and Skills Matrix
- ▶ Public Policy and Engineering Systems Synergy
- ▶ Roles and Skills of Engineering Systems Designers
- ▶ The Evolution of Complex Engineering Systems
- ▶ Transforming Engineering Systems: Learnings from Organising Megaprojects
- ▶ Transitioning to Sustainable Engineering Systems

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Design Perspectives, Theories, and Processes for Engineering Systems Design

3

Ola Isaksson, David C. Wynn, and Claudia Eckert

Contents

O. Isaksson (✉)
Department of Industrial and Materials Science, Chalmers University of Technology, Gothenburg, Sweden
e-mail: Ola.isaksson@chalmers.se

D. C. Wynn
Department of Mechanical and Mechatronics Engineering, University of Auckland, Auckland, New Zealand
e-mail: d.wynn@auckland.ac.nz

C. Eckert
School of Engineering and Innovation, The Open University, Milton Keynes, UK
e-mail: claudia.eckert@open.ac.uk

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Abstract

Engineering systems are socio-technical systems that provide solutions to fundamental economic and societal challenges. Such systems are complex in both technical and human terms. Engineering systems evolve over time, and uncertainty over time plays a decisive role. Perspectives on design, design theories, and design processes can be used to guide and support designers of engineering systems. This chapter provides an introduction to several well-established perspectives on design, such as design as participatory activity, design as unique mode of thinking, and more. In the same way design theories are introduced, exemplified by C-K theory, axiomatic design, domain theory, and others; and an introduction to well-known processes, including stage-based, agile, and set-based models and many more, is provided. It is explained how each of the discussed approaches offers valuable insights that help to address different aspects of complex systems design. The evolution of the approaches reflects the evolving recognition of users and context when designing engineering systems.

Keywords

Design · Design perspectives · Design theory · Design process · Engineering systems · Engineering systems design

Introduction

We live in a world in which the results of technology advancements are evident in our everyday lives. Human-made products and systems have a profound impact on how we live our lives, many of which have been realised by engineers doing design. Historically, engineering designers have focused on designing products that fulfil particular functions and perform in a particular way and that at the same time can be manufactured cost-effectively (see, e.g., Cross 2021; Pahl et al. 2007; Ullman 1992). However, products are increasingly seen as parts of larger systems, such that they cannot be designed in isolation. Designing these engineering systems involves consideration of how they behave and interact with users, with other products, and with society at large. Engineering design views engineering systems mainly from the perspective of the evolving product, with due consideration to its systemic context. Consideration of the socio-technical interactions and impact now needs to be an integral part of the design process of what is called an engineering system (De Weck et al. 2011). To design the engineering system in this wider context, design teams need to combine a broad range of skills and knowledge from within engineering disciplines as well as social, emotional, and cognitive skills and alongside economic and business skills and knowledge (see, e.g., Subrahmanian et al. 2020). The important role of design to address our societal and climate level challenges is now emphasised (Design Council 2021).

Over the years, engineering designers and design researchers have approached design from a number of perspectives, which provide complementary insights into different aspects of the design problem and have developed a number of theories that offer an abstract and generic view on design. They have also developed process models that describe both how design *is* done and how it *should be* done. This chapter discusses some well-established design perspectives, theories, and processes and their application to the design of engineering systems.

A good example of an engineering system, which we discuss throughout the chapter and we have also worked on, is an aircraft and its role as part of a transport solution. A century ago, the main design problem was how to master the flight physics of the aircraft itself (Vincenti 1990), ensuring that propulsive power was sufficient and that structural integrity was ensured. Today, the design challenge in air transport is to design and deliver a sustainable, zero-carbon transport solution within a few decades (see, e.g., Acare 2020).

Overcoming Disciplinary Boundaries in Engineering Systems Design

The theories and processes for engineering design have shifted over time from enabling design of the primary functions of a product or a system to include the system in relation to its social context. Traditionally, design theories and processes have focused within disciplinary boundaries – for example, design of mechanical systems by mechanical engineers, electrical systems by electrical engineers, aerospace systems by aerospace engineers, software by software engineers, and so forth. The disciplines involved in production developed their own theories and processes in, e.g., manufacturing, production, and maintenance engineering. Where user interaction is paramount, industrial designers and graphical designers seek to combine knowledge from social, human, and artistic domains into the design activity. However, it is becoming increasingly clear that the different disciplines need to be integrated to design engineering systems that meet the challenges of our time. These engineering systems also evolve. They are rarely defined from scratch, and once realised, they are subject to changes, upgrades, and addition of new functionalities throughout their operating lives (De Weck et al. 2011).

Another issue that has become more prominent in the engineering systems design context is that of coordination and collaboration in situations where many design teams need to design together. In fact, Smith (1997) identified that ever since the division of intellectual labour became more prominent through the industrial revolution, there has been a need to actively integrate disciplinary knowledge in design and development. As products relied on increasingly diverse and refined disciplinary expertise with their own practices, theories, and tools, the interdisciplinary design challenge also grew. Therefore, there has been an incentive to overcome barriers and facilitate cross-disciplinary design and learning. This has to an increasing extent impacted theories and processes applicable for more complex engineered systems. In particular, it is well known that as the complexity of a development task increases, more people, design groups, and organisations need to coordinate their work and share the same overall understanding of their undertaking. The complexity of the most complex products, like the moon rockets, has pushed collective human endeavour to its limits. Design theories and processes that are understood and shared are instrumental for success when developing these complex engineering systems. In this spirit, we see the design of engineering systems as discussed in this chapter to require the ability to define solutions that balance the behaviour of the forthcoming system, including how it interacts with its context.

Designers also need to define solutions for problems that are non-trivial and seldom well-formulated. This requires deep mastery of disciplinary knowledge while also combining and integrating contributions from many domains. Modern systems typically combine electrical, mechanical, and software subsystems that consequently require mechanical, electrical, and software engineering considerations in design while operating in regulatory and political contexts. Increased attention to human aspects and differentiation on markets has accentuated the need to include industrial designers and other artistic disciplines.

As products have become more interdisciplinary, complex, and interactive with their surroundings, they are increasingly seen as engineering systems themselves, in which the behaviour and performance of the system not only are determined by the behaviour of individual components, parts, and subsystems but increasingly by their interactions that contribute in important ways to the emergent behaviour of the system. Designing engineering systems thus requires overcoming disciplinary boundaries and combining a larger number of different disciplines than designing simpler products. As one of the consequences, design of engineering systems has embraced more abstract and generalised concepts such as architecture, modules, and platforms. Researchers and practitioners seek means to more effectively design for less concrete characteristics, the so-called ilities such as sustainability, maintainability, availability, and so forth (Ross et al. 2008). These issues and their interactions have always existed, but a greater focus on them during design has contributed to making systems safer, cheaper, and better-performing once in use. Overall, understanding how to design interactions and dependencies within and between systems is growing in importance. This is occurring alongside the growth in technology enabling connectedness (e.g., Internet of Things) and the increasing societal need for sustainable solutions.

Multiple Views on an Engineering System

To illustrate how products and systems can be seen in many different ways, we return to the example of the commercial aircraft and its interaction with, e.g., airport logistics. An aircraft is sufficiently complex to be described as an engineering system in itself but can also be conceptualised as a product and as a subsystem of a wider transportation system. The design and development of a new aircraft is a challenge in all its complexity, requiring the ability to make use of the latest achievements and advances in technology while always rigorously ensuring safety in the final product. A large aircraft has millions of parts and software modules that need to fit together and work together to fulfil the overall function of air transport. However, there is more to aircraft design. Aircraft manufacturers also need to meet expectations of passenger comfort while being ever more sustainable and of course being affordable and available for airline operations. Manufacturers need to provide increasingly complex solutions while improving production cost efficiency and reducing lifecycle costs. There is also a need for modern aircraft to interact with other aircraft and the air traffic management systems. Critical parameters of a modern aircraft are monitored in real time in communication with on-ground resources. In sum, therefore, an aircraft design team needs to find the best balance amongst stakeholder needs and expectations, some of which are in conflict and might be initially ill-defined. Therefore, as illustrated in Fig. 1, the task of designing an aircraft needs to be seen from many viewpoints but also must result in a coherent solution.

Overall, handling the complexity of such tasks and interactions requires a structured, systematic, and systemic approach to design, to assure that all relevant aspects are covered to a sufficient standard. Considering this challenge, the rest of this chapter is motivated by three questions:

- What are the main perspectives on design that together provide a rich picture of the topic?
- What are the dominant design theories and processes and where can I learn more?
- How are key insights into engineering design of use for engineering systems design?

Engineering Systems as Socio-Technical Systems

This section introduces some important concepts and terminology that will appear throughout the chapter. Firstly, what is meant by an engineering system? For this chapter, we adopt the definition of De Weck et al. who define engineering systems as "a class of systems characterized by a high degree of technical complexity, social intricacy, and elaborate processes, aimed at fulfilling important functions in society" (De Weck et al. 2011, p. 167). In our view, engineering systems design has two main dimensions: the technical and the social. This is represented in the framework depicted in Fig. 2.

In terms of the technical dimension, when designing a system, it is important to understand and define an initial boundary of the problem. Engineering systems have elements – *subsystems* – that when integrated define the characteristics of the system. Conversely, if the system is a part of a larger context and has clear interactions with that context, it is part of a system of systems, which according to Maier has two defining characteristics (Maier 1998, p. 271):

(1) Its component system[s] fulfil valid purposes in their own right and continue to operate to fulfil those purposes if disassembled from the overall system, referred to as "operational independence of the components".
(2) The component systems are managed (at least in part) for their own purposes rather than the purposes of the whole, referred to as "managerial independence of the components".

Fig. 1 Multiple views and levels of detail of aircraft systems design

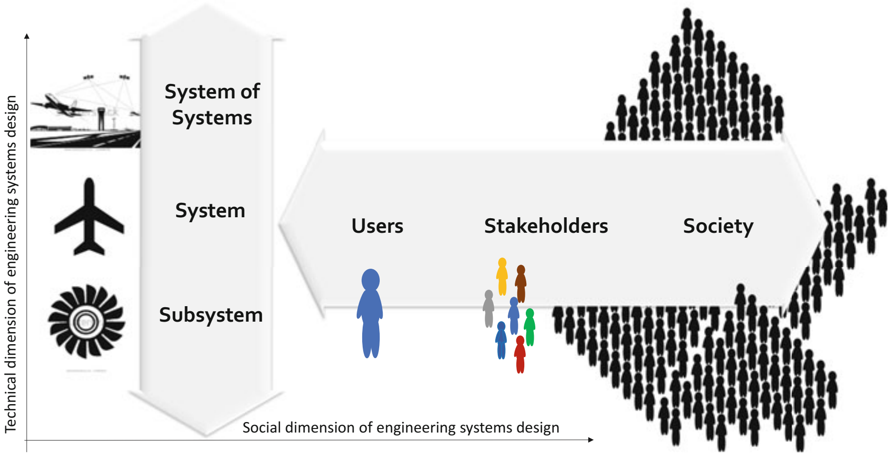


Fig. 2 Multiple levels of engineering systems exist in relation to social and technical dimensions, with needs and expectations on several levels

Adopting Maier's definition and applying it to our running example, an aircraft is a system, because it has its own purpose and is operated and managed in its own right. The aircraft interacts with other systems, such as airports, air traffic management, and fuel suppliers, to provide an aggregated function of transporting people or goods. An aircraft is thus a part of the air transport system together with air traffic control, on-ground logistics and infrastructure, and so forth. The air transport system qualifies as a system of systems.

An aircraft, as a system, consists of a large number of subsystems that in turn are organised into modules, parts, and components. The engine is, for example, one of about 18 different subsystems of an aircraft (the precise number depends on the level of decomposition) together with wings, fuselage, landing gear, and so forth. Each of these is typically complex enough to be labelled systems in their own right, but when viewed from the aircraft context, they are defined as subsystems. Meier (1998) argues that subsystems must operate independently, and following his definition, the aircraft is not a system of systems.

The distinction between *system of system*s, *system*, and *subsystem* also depends on the perspective of a particular design team and the target system they are focused on. For example, to the aircraft design team, an engine is a subsystem. But for the engine manufacturers, the engine itself is viewed as the target system – from this perspective, the aircraft is a higher-level system, while the individual parts of the engine are the subsystems. In other words, the definitions of system and subsystem are relative to particular designers, teams, or organisations. As long as a systemic view is beneficial, the division can be cascaded further. One challenge in designing engineering systems is that the behaviour of the targeted system and the system of systems in which it participates can be influenced by the behaviours of subsystems and their components on a much deeper level. In the case of aircraft, this becomes evident when failures occur and the underlying reason is found “deep down” in any of the many subsystems and their components. This is a well-known weakest link situation, and for aerospace products, certification authorities therefore require a fail-safe design strategy to avoid “any failure condition which would prevent the continued safe flight and landing” (Federal Aviation Administration 2020).

Complementing the technical dimension that is described above, our framework of Fig. 2 emphasises that engineering systems also have a social dimension. The social dimension represents the variety of actors who interact with the engineering system. Three categories of actor are shown in Fig. 2 and discussed in the next paragraphs.

The first category is the *user*. We note that the design process has at least two natural starting points: an existing design and the “users”, interpreted broadly. It is important to understand the users’ needs to design a system effectively. For an engineering system, there will usually be multiple user groups with different needs. The users of an aircraft would include the passenger, pilots, the crew, the maintenance personnel, etc. An example of a professional business actor falling into the user category is an airline that is also a customer of the manufacturer. Examples of users can often be clearly identified, each with individual needs and expectations that may or may not be well-defined.

The next category is the *stakeholder*. Stakeholders are those actors who are affected by, or have an interest in, the outcome of the engineering systems design. Users are a special type of stakeholder, and their needs need to be considered together with those of other stakeholder groups – in the aircraft example, these other groups include airport neighbours, certifying authorities, business owners in manufacturing companies, and suppliers. Each group has their own expectations and needs – that are likely to involve conflicting interest.

The third category of actor depicted in Fig. 2 is *society*. This represents even broader interests than stakeholders. Society can be represented by districts, regions, or global interests that communicate their needs and expectations via general means, such as conventions, agendas, laws, and directives. Societal needs apply to all actors and aspects of design. In aerospace, for example, the International Civil Aviation Organisation (ICAO) organises global and normative conventions in which states are members, where, e.g., flight safety statistics and safety plans for the entire air transport system are considered.

Societal needs and expectations have a direct link to all technical levels of an engineering system. An example in the aircraft design context is noise regulation that restricts noise emissions from flying. In this case, what is acceptable for humans living close to airports has been formulated as regulatory requirements that constrain all air transport actors by specifying allowable noise during certain times of the day around an airport. These regulations have influence on a system-of-systems level (e.g., on air traffic management – where and how to fly aircraft) and what noise emission levels are allowed from the aircraft itself, and the regulations are eventually cascaded down to design requirements on noise generating subsystems such as the engines. They can have a decisive impact on decisions made on lowest level of the system, e.g., enforcing noise reduction design solutions to components in the engine or constraining the aerodynamic envelope of the wings and fuselage.

Overall, engineering systems design must address technical issues on multiple system levels, and, in a similar way, designers must consider the social dimension of the engineering system on multiple levels, ranging from individuals to the global society. Design perspectives, theories, and processes can assist with these tasks.

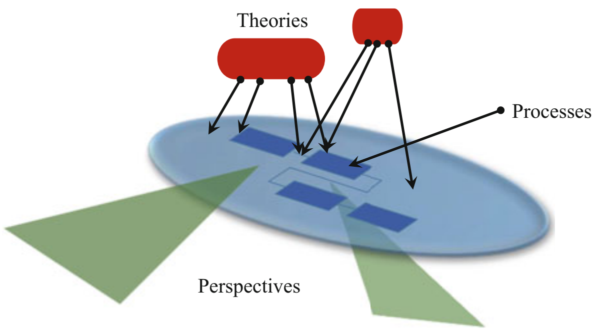
The Role of Design Perspectives, Theories, and Processes

The design of socio-technical engineering systems is a highly complex process without clear boundaries, which the different stakeholders approach in their own ways and from their own perspectives. Design, like any complex system, can only be understood in its entirety at a high level of abstraction or by adopting specific perspectives which shine a light on some aspects of design while subsuming others. The relationship between theories, perspectives, and processes is illustrated in Fig. 3. For the purposes of this chapter, we distinguish between *perspectives* on design, which each emphasises a particular aspect of socio-technical design, and *design theories*, which aim to be formal in the sense that the formality of an expression is defined as the invariance, under changes of context, of the expression's meaning (Heylighen 1999). Design theories are often intended to be general but are not predictive as theories in science often are. Design processes describe design in terms of common activities that characterise designing at different levels of detail, scope, and specificity. It should be noted that this is only one perspective – the design research community has not adopted a universally agreed distinction between perspectives, theories, and processes.

Design perspectives, theories, and processes collectively paint a picture of design and provide useful vocabulary, best practices, and tools and methods for people interested in the topic.

Firstly, to give some examples of *design perspectives*, design has been studied from the perspective of rational decision-making supported by mathematical tools to help evaluate alternatives and also from the perspective of the ways designers think

Fig. 3 Relationship between perspectives, theories, and processes



when they approach design tasks. These and other perspectives will be discussed in forthcoming sections.

Secondly, *design theories* are abstract conceptualisations of design as a generic process. Like any abstraction, each theory is a selection of elements for a specific purpose. A large number of different theories of design exist that each highlights a particular aspect of design, for example, in terms of the elements of technical systems or the status of the design knowledge generated at different points of the design process.

Design theories provide a lens onto difficult design problems and can thereby help to identify mistakes or omissions. In particular, theoretical concepts can be helpful for thinking through complex aspects of product development. For example, over recent years, many companies are increasingly making use of technology readiness levels (TRLs) (Mankins 1995) which provide a measure for how mature a technology is with regard to an industrial application. TRL1 denotes an innovative technology with a proof of concept, whereas TRL9 denotes a technology that has been applied successfully in operation. Many practitioners understand how to interpret TRLs and know, for example, that a TRL6 means that a technology has been validated in relevant environments, but not yet in the real context of use. This removes the risk of misunderstanding or long explanations, and for safety critical applications, TRL6 is typically required before committing to product development using a particular technology.

The boundaries between perspectives and theories are fluid; however, theories make an explicit claim to generality, whereas perspectives on design often imply generality by focusing on one aspect of design. The fascination that design holds for many researchers is that all of these theories and perspectives offer insight and still, when put together, are not enough to describe all aspects of engineering design. A range of influential theories will be discussed.

Thirdly, *design processes* present design fundamentally as a series of steps (or activities) that lead from a starting point, often needs or opportunities, to an ending point, often a designed product or system. These overlap with perspectives and theories where the latter imply steps in which designers in the broadest sense individually or collectively engage. Some influential design processes will be discussed from the engineering systems design viewpoint.

Perspectives, theories, and processes are often expressed through models, which as Stacey et al. (2020) analysed for process models have a complex relationship to the phenomenon they are modelling. They can be classified in many different ways. Wynn and Clarkson (2018) classify design and development (DDP) process models by their purpose and their scope. In terms of purpose, they define the following categories:

- "Abstract models convey theories and conceptual insights concerning the DDP. Such models have yielded important insights into design and development, and have inspired the creation of pragmatic approaches, but many of them do not directly offer guidance for practitioners.
- Procedural models convey best practices intended to guide real-world situations.

- Analytical models provide situation-specific insight, improvement, and/or support which is based on representing the details of a particular DDP instance.
- Management science/operations research (MS/OR) models use mathematical or computational analysis of representative or synthetic cases to develop generally applicable insights into DDP issues". (Wynn and Clarkson 2018, p. 164)

In terms of scope, they define another three categories:

- "Micro-level models focus on individual process steps and their immediate contexts.
- Meso-level models focus on end-to-end flows of tasks as the design is progressed.
- Macro-level models focus on project structures and/or the design process in context. This can include the overall form of a project or program, organisational and managerial issues relating to a DDP situation, and/or the interaction between the DDP and the context into which a design is delivered". (Wynn and Clarkson 2018, p. 164)

Recalling that design perspectives, theories, and processes are often expressed through models, this chapter focuses on the abstract and procedural models described above. Ideas expressed in the analytical and management science models will be discussed in other chapters of the book.

Design perspectives, theories, and processes have been strongly influenced by their application domains, such as urban planning, machine design, or information systems design as well as the education and traditions of the individuals creating them. The application domain also has a significant influence on the primary role that design plays and means that design is conceptualised in different ways, which are complementary but can be challenging to bring together as they use different vocabulary and set different priorities. To date, no single, unified perspective, theory, or process of design that fits all contexts has emerged. Rather, there are many approaches offering different and complementary views. It is certainly not possible to cover all aspects of design in a single chapter – in this case, the authors' background in mechanical engineering and design studies means that the chapter is grounded in these disciplines, whereas perspectives, theories, and processes relating to, e.g., software design or electrical design may be less evident in the chapter.

Design perspectives, theories, and processes can assist engineering systems design at all the levels indicated above by explaining, articulating, and prescribing how engineered systems are designed while also defining a set of concepts and a vocabulary that practitioners can use. Noting that some terms in the field are used in slightly different ways by different people, when describing each approach, we largely follow the terminology of the respective author(s).

Understanding perspectives, theories, and processes for design benefits from appreciating the evolving nature of design theories and processes. The different perspectives, theories, and process are often a reflection of the issues that concerned the products and periods in which their creators were working. In many ways, they evolve together with society itself. For example, systems engineering emerged in the middle of the last century when several engineered systems that still much influence our lives were created, such as the telecom industry, the computer revolution, mass air transport, and manned flight to the moon. Scientific breakthroughs in physics, chemistry, biology, and so forth enabled a range of technological innovations that are utilised in new products and systems by engineers. Mastery of technology was a route to success, and the systems engineering discipline emerged as a result of rationalising and explaining how to manage such technologically intense products and systems. For an overview of the history of systems engineering, see the previous chapter in this book. Since then, the globalisation of economy and the ongoing digital revolution have formed society into a more service-dominant logic in marketing (Vargo and Lusch 2008). The impact of the human way of living on our society and environment increasingly forms our society, where resource scarcity and ecological and socio-economic aspects grow in importance. Our ability to generate and process data, sometimes called the digital revolution (Brynjolfsson and McAfee 2011), is yet another cornerstone that drives societal development. There is also a clear trend that ownership of these engineering systems is no longer the natural choice for customers and users. We increasingly value what services and utility these products and systems can provide (Tukker and Tischner 2017). This has led to service-based business models where ownership of the engineering systems is no longer with the end customers and can be retained by the manufacturer. Naturally, these trends influence both what products and systems to develop and how these can be developed. Shifting societal values and new technological opportunities are explanations for the continuous update and evolution of design perspectives, theories, and processes.

Design theory contributes to meeting engineering systems design challenges as they have been developed to address multifaceted and ill-defined problems. On the one hand, theories, typically being generalised in nature, are often rewarding when analysing and understanding ambiguous situations. Theoretical approaches, including perspectives and processes, provide strategies to address real-world problems such as how to handle existing dependencies and constraints. On the other hand, interactions between a system and its context are largely neglected in most existing engineering design theories, and this is a current area of development. Applications of perspectives and theories into methods and practical implementations require greater consideration of the incremental and evolving nature of the practical development of engineering systems.

In summary, a vast number of theories, perspectives, and processes have been developed. There are complex relationships between them, and they can inform engineering systems design in a variety of ways. In this chapter, we focus on discussing a selection of design perspectives, theories, and processes (a) that have been influential in the field, (b) that have implications for engineering systems design, and (c) for which mature descriptions are available in English.

Overview of the Next Sections

The next sections provide an introduction to a selection of well-established design perspectives, theories, and processes applicable when designing engineering systems. Section "Theoretical Perspectives on Design" will discuss what is meant by design in the broad sense, unveiling some of the theoretical foundations and influential perspectives on design. Perspectives and theories provide insights and means to view and approach design problems, and their general nature makes them interesting for practicing and researching design, since "there's nothing as practical as good theory" (Lewin 1951). In section "Design Processes", we introduce design processes as a means to both understand and prescribe design and discuss how a selection of processes is relevant for design of engineering systems.

Such processes typically adopt principal strategies to understand and organise a design problem and prescribe how to work towards addressing that problem. Some design processes are of generic nature that makes them more generally applicable to different problems. As such, they may require a certain degree of training to master so that the key concepts can be appropriately applied to the specific problem and context studied. Other design processes may be specific to certain application domains and can be expressed even as norms that need to be followed for certain design situations. One example is the design of pressure chambers, where certain design processes need to be followed to comply with safety regulations. These latter types of design processes will not be treated in this chapter.

In section "Application of Design Perspectives, Theories, and Processes to Practical Case Examples", we discuss the utility of design perspectives, theories, and processes when designing engineering systems by raising how some of the challenges that are commonly faced can be met. Section "Conclusions" summarises important points to take away from the chapter.

Theoretical Perspectives on Design

Engineering systems design involves design at many different levels. As illustrated in Figs. 1 and 2, it ranges (for instance) from the details of components to the system of systems and from consideration of material properties to aesthetic appeal and stakeholder satisfaction. However, the practice of a designer of turbine blades differs from the practice of, say, an interior designer. There are similarities at a certain level of abstraction, but also significant differences, and yet the term design is used in both cases. This raises the question: what do we mean by design?

In his seminal book, *The Sciences of the Artificial*, the Nobel Laureate Herbert Simon defined design in perhaps its most general form as "to design is to devise courses of action aimed at changing existing situations into preferred ones" (Simon 1969). On a more detailed level, design has been conceptualised in different ways and from different perspectives, each of which has its own justification and advantages.

Design research and therefore the formulation of design perspectives, theories, and processes began to gather momentum after the Second World War. Over the period since then, research has moved focus from technical details, such as machine elements or geometric properties, to include a broader appreciation of the importance of the user and the wider system. This section first discusses what we mean by design before introducing eight design perspectives, which when taken together, give an impression of the rich phenomenon of design.

The Scope of Design

Design is an everyday activity that we all engage in all the time. We design when we decorate and furnish our houses, arrange our gardens, and throw together a quick dinner. When we make things without following detailed instruction, we design, for example, when we make clothes or carry out many DIY tasks. We also design our experiences, when we plan a holiday or a children's birthday party, where we pick existing offers and add our own to them (Papanek and Fuller 1972).

While everybody to some extent does design and can design, design is also a research discipline and a professional practice that can be studied. In fact, the study of design as a generic activity – as opposed to the study of some specific design domains – is a relatively recent addition to the academic canon. When the Open University in the UK launched a course in the late 1960s called "the man-made world" (The Open University 2020), this was a pioneering and influential effort in design education. The course was set out to teach design as a generic activity across different domains and highlighted the responsibility of designers for society and the environment. Mass distance education required a decoupling of design theory and design practice, where the theory needed to be made explicit and applicable to design in different domains and illustrated through examples in different domains. This work to identify what is generic about design processes across all different domains still continues (e.g., Daly 2008; Reymen et al. 2006). Less effort has been placed on understanding how design processes in different domains are different and why (Stacey and Eckert 2010).

Design research has typically perceived design as a generic process that applies to all design domains with the aim of identifying the common characteristics of all design problems and activities. However, individual researchers have approached design as a general subject from the viewpoint of their own domains, which has contributed to emergence of different perspectives in the discussion about design.

What is included in the term "design" is approached from two fundamental angles, often associated with design as a noun, referring to a product or the styling of a product, services, systems, solutions, and design as a verb. Also the scope of what is included in "design" varies. For instance, design can be viewed as the specific cognitive processes that are involved or as the entire collective effort of designing a complex system in and across organisations. Two other definitions of design are:

- "Everything that is associated with the design of a solution". According to this perspective, design is the process of creating artefacts or systems and involves many activities that in themselves would not be considered to be design. For example, designing an air transport system including the aircraft involves many scientific, mathematical, and administrative activities that, according to this perspective, would be considered parts of the design process.
- "Design as a unique activity". In this definition every task that is approached in a designerly way is considered design (Cross 1982). According to this perspective, design also applies to many everyday activities such as planning a dinner party or a solving a business problem.

The conceptualisation of design processes will be discussed in more detail in section "Design Processes".

The term "design" has its origins in the Latin term *designare* meaning 1. indicate/designate/denote; 2. mark; or 3. point/mark/trace out/outline/describe. From this comes the Italian word for drawing, *disegno*. In the sixteenth century, Giorgio Vasari introduced painting, sculpture, and architecture as the *arti del designo* (Burioni 2012). Italian and other European languages like German maintained the strong link between design and form-giving and have typically associated the term design with subjects that come from an art school tradition, such as product design, fashion design, or graphic design. In German, the term design is therefore focused on artistic aspects, while engineering systems design would be described as *Entwicklung*, i.e., development. The English term design is broader and encompasses any type of plan or specification for building of objects or systems and the process of creating such a plan. Consequently the English term design is applied to many different areas, much as mechanical design, industrial design or sometimes even systems engineering.

In recent years, design or design thinking has also been adopted outside of traditional product design domains. The highly influential Cox Review of Creativity in Business (UK Government 2005), commissioned by the UK government, puts it like this: "design is what links creativity and innovation. It shapes ideas to become practical and attractive propositions for users or customers. Design may be described as creativity deployed to a specific end". This is based on definitions that "Creativity is the generation of new ideas – either new ways of looking at existing problems, or of seeing new opportunities, perhaps by exploiting emerging technologies or changes in markets" and "Innovation is the successful exploitation of new ideas. It is the process that carries them through to new products, new services, new ways of running the business or even new ways of doing business. This has moved design and creativity into the centre of public discourse in the UK and argued for supporting creative industry as one of the drivers of UK economy (Design Council 2018). The definition adopted for the creative industries as those industries which have their origin in individual creativity, skill and talent and which have a potential for wealth and job creation through the generation and exploitation of intellectual property" (DCMS 2001, p. 4). They included not only traditional design fields such as architecture and artistic design domains such as product design, graphic design, or fashion but also the creation of cultural artefacts such as advertisement, media, music, visual arts, and publishing. This included aspects of software design and IT, such as games design. This definition goes back to a study by Caves (2000), who investigated industry sectors in which the participants were driven by a passion for what they do and put up with a very uneven pay for similar tasks.

Overall the scope of *design* is wide, with a clear movement to embrace design as a problem-solving and solution seeking approach for everyone. Recognising the commonalities and differences between different approaches can help to use them in a constructive way. In fact, engineering systems design combines many different aspects of design. The engineering challenges apparent when designing engineering systems require deep technological and scientific knowledge, as well as means to represent, manage, and control the evolution of complex systems such as aircraft and their interactions with users, stakeholders, and society.

Theory Meeting the Challenges of Design

Thinking about design has a long and august history. Aristotle (2014) draws (in his work on physics) a fundamental distinction between natural products, which are driven by processes of nature, and artefacts that are created by humans and will eventually vanish without human interventions. For many centuries, what we would now call complex products, such as aqueducts or cathedrals, were designed by people who learned their job as apprentices and acquired engineering knowledge as tacit knowledge (Ferguson 1992). Throughout the centuries, engineering knowledge has been developed and formalised to meet the needs of engineering designers (Vincenti 1990). Thereby the focus shifted with the products of greatest concern at the time.

Renaissance books of mechanisms, as well as drawings and descriptions of machines, were systematically published and shared (Ferguson 1977). The first texts on engineering design can be found in the early nineteenth century, notably in the wake of setting-up the first technical universities, e.g., Ferdinand Redtenbacher (1848), who pointed out that machine-related knowledge alone is not sufficient. Effective design also requires a talent for invention and an understanding of the mechanical process that the machine must serve. A modern engineering systems designer would recognise technical knowledge, creativity, and an understanding of purpose and context as the constituent elements of successful engineering design. Since the Second World War, engineering design has become more structured and increasingly more based on mathematical and computational analysis (Ferguson 1992). Consequently, engineering design and its methods have today become very strongly influenced by the capabilities of the computational tools that support it.

In the middle of the twentieth century, architectural design was a major driver of design theory development. For example, Alexander (1977) developed the idea of patterns in design, representing similar solutions at a fairly high level of abstraction. Computer science as a discipline developed some of its own theoretical foundations for design while drawing on general design theory, for example, the idea of software patterns built on Alexander's ideas (Gamma et al. 1994). More recently, many of the different design research communities have fragmented and have developed their own vocabularies. Bringing the concepts, ideas, models, and methods of these different communities together is one of the challenges of future engineering systems design. This is much-needed to meet the expectations for design of engineering systems, in which the interaction with the system context becomes an essential issue to be considered during design.

Perspectives on Designing for Engineering Systems

As the scope of design research has broadened from the design of mechanisms and products to a systemic view, which considers not only products but the way we interact with them, the way design has been conceptualised has changed accordingly. In this section, we discuss different perspectives on design, each of which is helpful and useful yet only offers a partial view on design from the engineering systems perspective.

Design as Decision-Making

Design can be viewed as a process of making decisions that can be optimised by mathematical modelling and by applying principles of decision theory (Chen et al. 2012). In brief, this can involve specifying a problem in terms of constraints and objectives, identifying feasible solutions allowed by that problem definition, and determining which solution offers maximum value.

Hazelrigg (1998) writes that viewing design in this way can help to ensure that important decisions are made rationally while taking into account the broader context, including the total lifecycle of the product or system. Thus, the decision-based design perspective is especially pertinent to engineering systems design. One challenge in applying this approach is the high complexity of many real design problems, which necessitates simplification to make decision analysis tractable. Another challenge is appropriately evaluating solutions, considering how to identify and value conflicting stakeholder preferences and how to account for unpredictable or changing contexts of use. The sequence of decisions may affect the result, and some decisions may need to be treated concurrently (Mistree et al. 1993). Decisions are also made on different system levels, having the same originating top-level requirements. Hence requirements need to be systematically decomposed, or cascaded, while maintaining the original intent (e.g., Kim et al. 2003). These and other aspects of decision-based design have been studied by a number of researchers (e.g., Chen et al. 2012).

One approach to dealing with the uncertainties endemic in engineering systems design while optimising design decisions is to apply real options theory, e.g., Cardin et al. (2017). Current research into decision-making systems in design also often emphasises the need for visual analytics as an interactive way to allow decision-maker greater involvement and appreciation of the limits and trade-offs (Keim et al. 2008).

Design as Rational Problem-Solving

In 1969, Simon published his book *The Sciences of the Artificial* (1969). He distinguishes science, as concerned with what is, from technology, which is concerned with changing into preferred situations. This puts the desire to change and to improve at the heart of design, viewed as the activity that creates technology. Bunge (1966) sees technology as applied science in the sense that technology is about action that is underpinned with science unlike arts and craft. However, design has always stood between science and arts and crafts. This tension has dominated the debate on how design is conceptualised and how the rhetoric around design is constructed by different groups.

Simon also puts forward a view of design as a rational problem-solving process applied to ill-defined problems. The principles of bounded rationality (Simon 1957) limit the designer's ability to explore solutions. For most design problems, it is simply not possible for a human to fully gather all relevant information, explore all potential solution, and then settle for a best solution, so that designers "satisfice", i.e., settle for a satisfactory solution rather than look for a best solution. He famously states that "everyone designs who devises courses of action aimed at changing existing situations into preferred ones" (Simon 1996 p. 111). Simon (1969) argues that complex problems are *almost decomposable*. The overall design problem decomposes into smaller problems, which are connected and influence each other.

The perspective that design involves (or should involve) a rational approach to problem-solving is embedded in many widely accepted design processes and practices, for example, by stipulating that a designer should progress from abstract considerations to more concrete ones or should seek to generate many possible solution concepts before selecting the best according to defined criteria.

Design as Reflective Practice

In 1983, Donald Schön published his book *The Reflective Practitioner* (1983). A number of architects were given the problem to design a school from scratch. As they sketched their designs, it became apparent that their behaviour was a mixture of making marks and then looking at them – reflecting about what they had done. When looking at the paper, they engaged in two different kinds of seeing, "seeing that", i.e., recognising something, and "seeing as", i.e., interpreting what they saw (Schön and Wiggins 1992). Schön called this process "a conversation with the situation". The inherent ambiguity of sketches affords different interpretations of the same marks, and a designer is able to distance themselves sufficiently from their work to interpret design elements in different ways and use these as a starting point for a different design trajectory. Schön summarised this as an abstract cyclical process of:

- Naming: recognising an element as a meaningful entity and giving it its name at a suitable level of abstraction, e.g., calling a connected line a "square" or a "swimming pool"
- Framing: in which different named objects are pulled together into a more general problem frame

- Moving: in which the design is advanced within the current frame
- Reflecting: in which the design is evaluated before the next cycle begins

Schön brought in perspectives on how to deal with the complexity of engineering systems by iterating between the abstract and the concrete based on the current state of design.

Design as Addressing Wicked Problems

Many design problems fall under the category of wicked problems, a term coined by Rittel and Webber (1973, p. 161). They state: “The formulation of a wicked problem is the problem! The process of formulating the problem and of conceiving a solution (or re-solution) are identical, since every specification of the problem is a specification of the direction in which a treatment is considered”. They argue that wicked problems have the following characteristics:

1. There is no definitive formulation of a wicked problem.
2. Wicked problems have no stopping rule.
3. Solutions to wicked problems are not true or false, but good or bad.
4. There is no immediate and no ultimate test of a solution to a wicked problem.
5. Every solution to a wicked problem is a “one-shot operation”; because there is no opportunity to learn by trial-and-error, every attempt counts significantly.
6. Wicked problems do not have an enumerable (or an exhaustively describable) set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan.
7. Every wicked problem is essentially unique.
8. Every wicked problem can be considered to be a symptom of another problem.
9. The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problem’s resolution.
10. The planner has no right to be wrong.

Rittel and Webber looked at town planning as an example of a wicked social problem that required a social action that could lead to a change of human behaviour and ameliorate the underlying problem. While it is debatable whether all design tasks have all these characteristics, many of the problems addressed by engineering systems design certainly do. Buchanan (1992) argues that “design problems are ‘indeterminate’ and ‘wicked’ because design has no special subject matter of its own apart from what a designer conceives it to be”. He sees this as in fundamental contrast to science, which he views as being concerned that principles, laws, and rules are necessarily embodied in subject matter. According to Buchanan, a designer operates on two levels: a general level, on which the designer forms ideas and hypothesis about the nature of products or the artificial word, and a practical level, being embedded in specific circumstances. In engineering systems design, many of the problems are incremental, i.e., existing solutions need to be upgraded or incorporated into a new version of the design, which makes many of the design problems both partially over- and partially under-determinate. In the process of understanding and addressing, designers need to make sure that their problems are sufficiently well defined to address them. Engineering problems are in practice often over-constrained, while many artistic design problems are underspecified, so that designers embark in a constraint-seeking process to limit their options (Stacey and Eckert 2010).

There are many examples of wicked problems in engineering systems design, especially in system-of-systems issues that involve people. For engineering systems design, it is unlikely that there are any "true" or even "optimal" solutions, but rather there are a range of alternative solutions that are better or worse for the situation. For instance, an aircraft has a range of conflicting objectives to deal with, both on the engineering level with safety or comfort and weight and fuel efficiency. To assess the goodness of the aircraft, the external conditions such as how and where to operate the aircraft, passenger load factors, turnaround time at airport, etc. need to be included. The interaction between the aircraft as a system and its context becomes a part of the engineering systems design. This illustrates how engineering systems design thus qualifies as a wicked problem according to Rittel's criteria.

Design as a Unique Mode of Thinking

Cross (2006) carried out many interviews with famous designers to identify characteristics of their way of thinking, which he concludes goes beyond what ordinary designers or lay people would engage in. He termed this designerly thinking, taking a cognitive approach to how excellent design practitioners do design. This work represents some of the academic underpinning of the wider design thinking movement that is described in section "Design Thinking as a Universal Approach"

Cross identified the following characteristics of designerly thinking:

- Rhetorical and exploratory: a designer explores and might break new ground and therefore might need to persuade colleagues or clients of the merits of the new design. To illustrate the rhetorical nature of design, Cross cites the architect Denys Lasdun (1965): "Our job is to give the client . . . not what he wants, but what he never dreamed he wanted; and when he gets it, he recognizes it as something he wanted all the time".
- Emergent: design problems are ill-defined, and as already discussed, designers reframe the problems many times throughout the design process. Cross quotes the architect Richard MacCormac (1976): "I don't think you can design anything just by absorbing information and then hoping to synthesise it into a solution. What you need to know about the problem only becomes apparent as you're trying to solve it".
- Intuitive and abductive: designers build conclusions based and partial information. Rather than having a full understanding of a problem, they lead formats to proposing a new solution. They see links between ideas that other would not. See, e.g., Dorst (2011).
- Reflective: designers engage, as argued by Schön, in a dialog with external media.

- Ambiguous and adventurous: designers can live with uncertainty and push the limits of what has been done so far or what would be expected of them. This also can entail a certain personal risk as they put their judgment at stake.

Design Thinking as a Universal Approach

The problems facing designers of engineering systems are often wicked, and there is rarely an obvious way forward. Typically, there are multiple stakeholders involved who may have conflicting interests. An overly systematic way to address such problem can easily get trapped in excessive and complex analysis efforts, without ensuring a successful outcome. Design thinking, according to Buchanan (1992, 2019), takes another approach to address such problems from a collaborative and co-creative view, which welcomes ambiguity. It stresses the coevolution of the design problem and the design solution, in which designing is seen as a way of understanding the problem and analysing the problem influences the design. Design thinking emerged as a problem-solving approach during the 1980s and has increased in popularity over the last decades, partially through the commercial success of companies such as IDEO and the applicability to address open problems in a wide range of disciplines. Brown (2008) also being the president of IDEO describes designing as an iteration between three pillars: inspiration, ideation, and implementation. In the inspiration phase, the emphasis lies on finding needs and opportunities and stresses observation and preferably presence of users, seeking to understand also "extreme" users. The idea is to both identify opportunities and see problems as sources of inspirations. A range of simple methods have been developed to support design thinking activities, many of which welcome interaction, building on each other's ideas and viewing the task from different perspectives as means to liberate creativity (Gordon et al. 2019).

The design thinking approach following the d.school at Stanford builds on five phases as below (Plattner et al. 2009):

- Empathise, the starting point by observing user preferences and discovering the user needs
- Define, is about building awareness and gaining a deeper insight in their core problems and what opportunities may exist
- Ideate, is the most creative phase. Usually a team exercise that embrace both quantity and quality of ideas of solutions
- Prototype, following direct after ideation phase, by prototyping the ideas quickly (sketches, paper models) and building on each other's ideas
- Test, is the phase where prototypes are matured through testing and learning what works and does not

Design thinking as a universal problem-solving approach has gained significant recognition also outside the design research community as a means to utilise knowledge from "non" designers and engage users and stakeholders. As such, it has attracted attention in the business community (see, e.g., Liedtka 2018). What is less emphasised in design thinking is the often extensive engineering effort necessary to both define and evaluate the solutions (i.e., the test phase) where the situation so requires. In engineering, design thinking is usually employed in under-constrained or ill-constrained situations, where user engagement is also a means of getting user buy in for a future solution. Design thinking is less well suited to over-constrained technical problems, for example, in the turbine blade design within the aircraft design example.

Design as a Participatory Activity

An age-old criticism targeted at designed objects, in particular buildings and complex systems, is that users do not like them, and their needs are only partially met. This has given rise to the desire to involve users in the design process through what is called participatory design (Sanders et al. 2010), which is also closely related to cooperative design and codesign (Sanders and Stappers 2008). This approach is particularly prominent in architecture. Sanoff (2010) offers the following definition: "Participatory design is an attitude about a force for change in the creation and management of environments for people. Its strength lies in being a movement that cuts across traditional professional boundaries and cultures. Its roots lie in the ideals of participatory democracy". Participatory design allows the user to be an active member of the design process and to improvise and create themselves as a means of discovering their own needs and desires for the object. Being part of the creation process also increases the willingness of users to accept the eventual result. However, the challenge is how to engage users at different stages of the process. At the beginning, the collection of needs, constraints, and requirements can be very abstract and difficult to express making it difficult for users to engage with the associated partial and abstract representations. Users often engage by critiquing early design suggestions, at which point many fundamental decisions are already taken and the users are biased by the visualisation they see. Later in the design process, information can become highly technical, so that users might not be able to understand the full implications.

Participatory design also plays an important role in computer science, which has developed multiple methods for how to engage users (see Kensing and Blomberg 1998 for an early influential discussion). In computer science, this has given rise to movements, such as user-centred design (Norman and Draper 1986; Sharp et al. 2019) or "extreme programming" processes, which amongst other elements advocate frequent iteration loops with users, so that user can comment on parts of a computer systems and generate new requirements. In agile development, this has given rise to well worked-out methodologies for user engagement (Beck et al. 2001, Hartson and Pyla 2012).

Participatory design deemphasises the technical aspects of design, which designers carry out almost behind the scenes. It is particularly valuable for design problems where the response by users (or category of users) is decisive for evaluating design alternatives.

Design as a Holistic Activity Beyond the Artefact

A product-service system (PSS) recognises that the value of an engineering system typically is associated to how well it performs in use, when provided as a service.

Product-service systems equally acknowledge that the service provided depends on the characteristics of the product or system that enable service provision. Baines et al. (2007) provide a summary of PSS concepts, which all share the central theme that a PSS is an integrated combination of products and services. Designing a PSS solution requires both services and the physical artefact to be designed together with the business design.

Early definitions of PSS emphasised the environmental advantages of combining products and services together such as Mont (2002), since the PSS model incentivises business to be more resource aware and enables shared use of (sub)-systems across PSSs. According to Mont (2002), “PSS is a system of products, services, supporting networks and supporting infrastructure that is designed to be competitive, satisfy customers’ needs and have a lower environmental impact than traditional business models”. Another definition is offered by Tukker and Tischner (2017) who defined first the product-service as “a value proposition that consists of a mix of tangible and intangible service design and combined so that they jointly are capable of fulfilling final customer needs” and, second, the PSS as the “product-service including the (value) net-work, (technological) infrastructure and governance structure (or revenue model) that produces a product service”.

How to design PSSs is still theoretically immature (Isaksson et al. 2009), yet the PSS business logic is highly attractive for businesses. Some of the apparent challenges of designing PSSs are (i) their intangible nature, following inclusion of services; (ii) the tangled relation with business and technology; and (iii) the lack of concise ways to evaluate the quality and value contribution of the PSSs. A service can be designed in advance and thereafter delivered as it is consumed by its customer. The evaluation of service performance requires therefore the customer response and perception to be included and makes the customers an integral part of the evaluation process. The PSS concept fits well with the increased ability to monitor data in use and sense how products and services are working, using IoT (Internet of Things). In recent years, the interest in PSS has broadened from an initial focus on sustainability to a perspective that brings together physical products with digitalisation technology and circular business models.

Section Summary

The eight different perspectives of design that have been described in Subsections “Design as Decision-Making”, “Design as Rational Problem-Solving”, “Design as Reflective Practice”, “Design as Addressing Wicked Problems”, “Design as a Unique Mode of Thinking”, “Design Thinking as a Universal Approach”, “Design as a Participatory Activity”, and “Design as a Holistic Activity Beyond the Artefact”, have arisen, in part, because researchers have focused on different aspects of design problems. Figure 4 illustrates a possible mapping between these design perspectives and the elements of engineering systems design that were presented in Fig. 2. In particular, design as decision-making (section “Design as Decision-Making”) arose from trying to select solution alternatives, such as the selection of a suitable compressor and turbine blade geometry, where objective and measurable criteria apply. Design as rational problem-solving (section “Design as Rational Problem-Solving”)

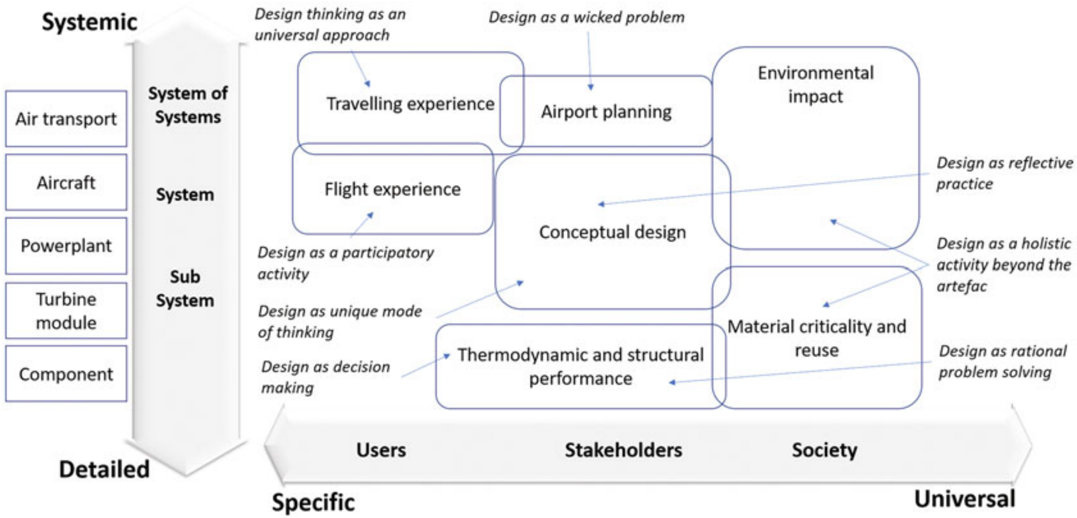


Fig. 4 The eight design perspectives discussed above are mapped to the classification from Fig. 2

emphasises a broader problem, but one with goals and structure. Design as reflective practice (section "Design as Reflective Practice") and design as a unique mode of thinking (section "Design as a Unique Mode of Thinking") both highlight the importance of holistic and tacit thinking in design that goes beyond what can be mathematically modelled. For example, this is highly relevant when describing early conceptual design before equations are available. Design addressed as a wicked problem (section "Design as Addressing Wicked Problems") highlights that in many design problems, the solution ought to work first time. For example, an entire airport can be prototyped and – as the infamous new airport in Berlin illustrates – getting it wrong is highly costly (Fiedler and Wendler 2016). Recently these ideas have been broadened to designing the product and the processes in conjunction. What all these conceptualisations have in common is that they focus on the designer as a trained professional. The design thinking as a universal approach (section "Design as a Unique Mode of Thinking") brings the user explicitly into a co-creative design process. In participatory approaches (section "Design as a Unique Mode of Thinking"), the user is the expert of its own needs, who can give feedback to the designer, whereas design thinking focuses on appreciating needs and generating innovative solutions. Both these focus on user experience and are less applicable for constrained safety critical applications. For such design, e.g., sizing and optimisation of reliable and efficient machinery, rational design strategies and decision-based design are more applicable. Complex designs involving lifecycle aspects and sustainability performance are candidates for design beyond the artefact (section "Design as a Holistic Activity Beyond the Artefact") (Fig. 4).

Design Theories and Engineering Systems Design

We now move on from the discussion of design perspectives to the discussion of selected design theories of value to engineering systems design. These theories have several purposes, such as helping to establish a common vocabulary, to provide a background to tools and method development for design, and to frame design engineering design education. Different theories coexist, and a dominant paradigm is yet to evolve.

Design theory has evolved as a field of its own to investigate general questions about design in the abstract, such as "what are the core phenomena of design? Is the discipline Design driven by novelty, continuous improvement, creativity, or imagination?" (Le Masson et al. 2013). Typically, theories aim to explain the phenomenon of design in its entirety, and many theories derive prescriptions how design should be done from their conceptualisation of design. Design theories are not just theories about what design is but in some cases also theories of how it should be done. Many of the theories are at the same time descriptive and prescriptive. Therefore, the term theories blurs into processes described in the following section. The authors themselves also variously refer to their theories as models, processes, frameworks, or ontologies. Design theories are general in nature and as such should be distinguished from investigation of specific design issues from a theoretical perspective (e.g., Vermaas' work on function in design, e.g., Vermaas (2013) or Eckert and Hillerbrand's (2018) work on models in design).

The rest of this section gives a brief overview of five influential theories of design that have been introduced over the last 50–60 years in the design research community. They also illustrate how theoretical development has evolved together with influential societal and scientific trends, increasingly emphasising universalism, abstraction, interventions, and systemic thinking. There are also many other established theories, each offering internally coherent frameworks and individual sets of vocabulary that help to think about design in a consistent way.

The first theory to be mentioned is the theory of technical systems (TTS) (Hubka and Eder 1988) central to their framework for design science (Hubka and Eder 2012). This conceptualises a technical system as one in which a collection of engineering design activities, such as generating, retrieving, processing, and transmitting of information about products are applied to abstract descriptions of technical systems at different levels of detail as well as production process tasks, such as production planning, need to be carried out and economic, business, and societal issues need to be considered. A fundamental view is that design is about transforming something, called an operand, from an existing state to a desired state through a socio-technological transformation system. The operand comprises material, information, and/or energy states. The transformation system comprises of operands that are either human systems or technical systems that execute the transformation in an active environment, represented by the information system and the management and goal system. This system is shown in Fig. 5. TTS provides models for how energy, material, and information are transformed through the transformation process by the operands (see Fig. 5).

Inspired by Hubka and Eder (1988), Andreasen (1980) introduced the domain theory where the basic idea is to view a product as systems of activities, organs, and parts and to define structure, elements, behaviour, and function in these domains. This inspired, e.g., Malmqvist (1997) and Mortensen (1999) to formally separate functional requirements from the means (design solutions that realise the functions) in a way encouraging formal modelling of design alternatives and customising configured products. For an update of domain theory, see Andreasen et al. (2014).

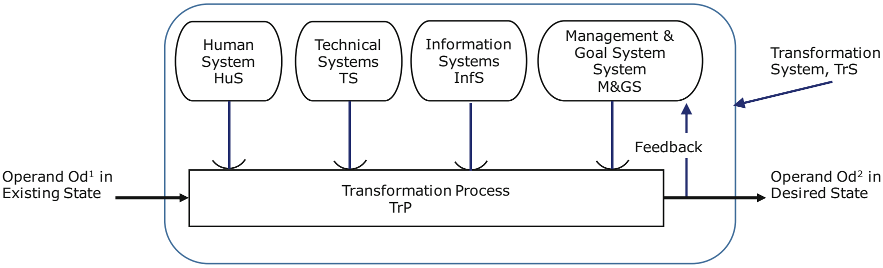


Fig. 5 The transformation system for design, as described by Hubka and Eder (1988)

The TTS and its derivatives provide a systematic way of describing technical systems and introducing the ability to share an understanding of systems and processes from different perspectives. Hubka and Eder provided a comprehensive perspective on the elements of design and designing and pointers to universal solution principles. The domain theory by Andreasen and its derivatives strengthened ways to architect products and systems from their functional elements which have influenced systems modelling tools.

Secondly, axiomatic design (Suh 1990) also describes design as a transformation of functional requirements into design parameters. Design is seen as a bootstrapping process where the functional requirements and design details are developed in increasing levels of definition, and functional requirements at a lower level of resolution are defined in response to design implementation decision already taken. It maps functional requirements to design parameters in matrices and advocates that designs should have a clear and separated mapping between functional requirements, as the multiple functions being carried out by the same product elements introduce risk. In doing so, axiomatic design holds that designers should adopt two axioms:

- The independence axiom. Maintain the independence of the functional requirements (FRs).
- The information axiom. Minimise the information content of the design.

The axiomatic design theory provided a perspective on how to deal with the complexity of design, based on systematic decomposition of systems and linking in how elements of systems fit into a functioning unity. To systematically separate out what the solution does (FRs) from what it is helps designers to avoid being overly influenced by preconceptions. Designing compliant to axiomatic design principles can be beneficial in particular for modular designs. These issues of modularity and complexity are central for engineering systems design.

Thirdly, the widely used FBS ontology proposed by Gero (1990) argues that design can be described through three classes of variables:

- Function (F) variables, which describe the teleology of the object, i.e., *what it is for*
- Behaviour (B) variables, which describe the attributes that are derived or expected to be derived from the structure (S) variables of the object, i.e., *what it does*
- Structure (S) variables, which describe the components of the object and their relationships, i.e., *what it is* (Gero and Kannengiesser 2004)

According to FBS, designs are generated through the iterative application of eight processes (the arrows in Fig. 6) to these variables: formulation, synthesis, analysis, evaluation, documentation, and reformulation of the function, structure, and behaviour (see Fig. 6). Gero and Kannengiesser (2004) develop this further to reflect the situatedness of human cognition and applied to processes (Gero and Kannengiesser 2007). While the definition of function in FBS is intuitive to native speakers to

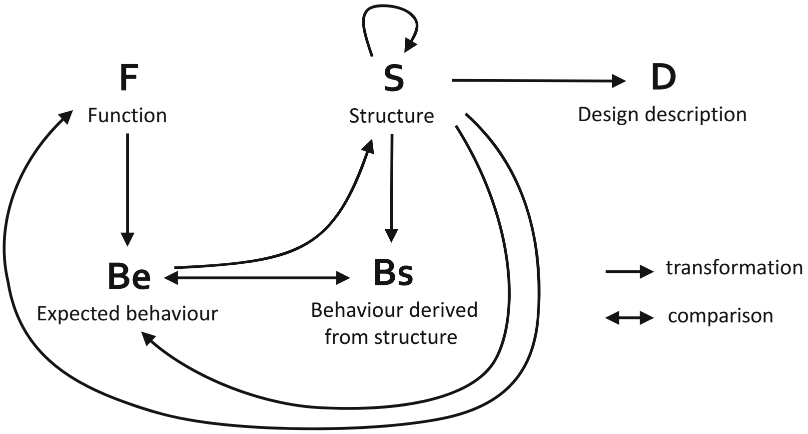


Fig. 6 The function-behaviour-structure framework, redrawn from Gero and Kannengiesser (2004)

English, other notions of functions with associated theoretical frameworks exist (see Vermaas 2013; Crilly 2010).

FBS brought a consistent framework for associating design variables to processes for reasoning about, and determining, desired behaviour of what is being designed. FBS is applicable to design activity on all levels of engineering systems, as shown in Fig. 2.

Fourthly, C-K theory (Hatchuel and Weil 2009) claims to be a unified and formal design theory that argues that design can be modelled as the interplay between two interdependent spaces: the space of knowledge (K), which contains the propositions that are validated or assumed to be true, and the space of concepts (C), which are (yet) undecidable. The design process generates both knowledge and concepts and can be seen as moving between these spaces:

- K to C (disjunction): a concept is proposed based on knowledge.
- C to C (expansion): a concept gives rise to a concept.
- C to K (conjunction): a concept becomes established knowledge.
- K to K (expansion): new knowledge is derived from existing knowledge.

The C-K theory focused on the appreciation of expansion of knowledge being generated and matured through the design. It expresses the fact that design is an interplay between the proposition of new ideas followed by testing and evaluation of the ideas to mature solutions.

Finally in this subsection, the fact that design is a social process that carried out a rich context is explicitly included in the PSI framework (Reich and Subrahmanian 2020). The PSI framework holds that design plays out in three different spaces that need to be considered together:

- The problem space ("What is being designed?") covers the object that is designed and the process required to do so.
- The social space ("Who are stakeholders in the design?") covers the motivations and aspirations of those involved in the creation, use, and maintenance of the artefact.
- The institutional space ("What is the institutional context in which the design is conceived, implemented, and operated?") covers the economic, managerial, organisational, and political contexts that influence the product over the life cycle.

These spaces are connected, and changes spread between them. If the spaces are misaligned, problems can occur, which in turn might become a design problem in their own right. PSI makes explicit that design is a socio-technical processes and that failure of design projects is not necessarily caused by problems with the product but can arise from a lack of understanding and effort invested into the social and institutional space.

PSI represents recent contributions as an engineering design theory addressing societal interaction and that the design goes way beyond the product. The effect of design requires the interaction with its context to be adequately designed as well.

In summary, the five influential design theories have been selected as they cover a spectrum, ranging from the specific and artefact focused to the system of systems and wider societal aspects. This also follows a chronological order of when they have emerged. In other words, initially, engineering design theories focused on technical challenges, whereas more recently, design theories also address the interactions with society and other systems. Some approaches are intuitive and heuristically defined, such as Suh's axiomatic design principles (Suh 1990), while others focus on categorising and organising design as a scientific discipline (e.g., Hubka and Eder 2012). Yet others focus on what is being designed (e.g., Gero and Kannengiesser 2004) or the tension in knowledge exploration in the C-K theory (Hatchuel and Weil 2003). In short, most theories offer a perspective and serve to bring a structure for understanding and clarity from this perspective and to its governing context.

For more comprehensive lists, comparisons, and discussions of engineering design theories, see, for example, Le Masson et al. (2013), Eder and Weber's (2006), or Chakrabarti and Blessing (2014).

Design Processes

Processes of creating and developing designs can be viewed, broadly, as descriptions or prescriptions of how the activity of designing unfolds over time (or is thought to unfold or expected to unfold). Design processes complement design perspectives and theories by providing more explicit guidance on how to approach design. By encapsulating philosophies of how the work should be done and organised, process models may help to align process participants and their mental models. They are, therefore, important enablers of design coordination, which becomes more important in situations of high complexity – common in the engineering systems context. Process models depicting best practice (of generic or specific nature) are valuable to convey insights about how to do design and how to organise it and so are an important tool in education and training. Such models are helpful to prescribe and understand design, as well as to control, manage, and align design work in and across organisations. Some of the main value of a process is simply to communicate how to do design work, which is especially useful where the task at hand is new to the designer or infrequently encountered. Processes also help to avoid overlooking important steps or issues in a particular design context.

Research and practice have considered design processes from various perspectives. In this section, some well-established design processes are introduced, and their relation to the perspectives and theories mentioned above is discussed. The process models discussed here originate mainly from mechanical engineering design and engineering product development, but as will be explained, many of the insights in the processes are applicable to the engineering systems design context.

The term process is used in various ways in colloquial and research language. It is sometimes used to refer to what actually happens during design and sometimes – perhaps more frequently – used to refer to the particular steps and their organisation that are supposed or expected to be followed. For this chapter, it is important to carefully distinguish between the process itself and a model of that process. A process model is in essence a simplified representation of a process that focuses on specific issues deemed important by the model's creator, helping to communicate those issues while leaving others out. The following section discusses design processes as represented in some well-known explicit process models.

The discussion of process models in this section is organised broadly around the classification of such models presented by Wynn and Clarkson (2018). These authors write that process models consider the design and development process at three levels, namely, the micro-level, meso-level, and macro-level. The distinction between these levels focuses on the scope of the process considered by a particular model, which is not necessarily the same as the number of people involved and the timeframe or the scale of the design situation. To recap from section "Introduction", micro-level models emphasise individual activities and their immediate contexts. Meso-level models concern end-to-end flows of work related to the progression of a design. Macro-level models concern the interface between the design process and its context, including project structures.

Aside from scope, process models come in different types aligning to the purpose intended for the model. The present section focuses on only one of the model types and purposes: procedural models, which are intended to provide best practices for design and development in the context of engineering systems. Abstract models provide conceptual insights (the design theories described earlier often incorporate abstract process models). The other two types of process model, namely, analytical and MS/OR models, are intended to represent specific situations or classes of situation to generate situation-specific or general insights for improvement. These two types of model are outside the scope of this section, but some are discussed elsewhere in the book.

There are numerous process models of each type and at each level of scope. Noting that the focus of this section is on engineering systems design, the framework presented by Wynn and Clarkson (2018) is reinterpreted for this context in Fig. 7. The figure indicates how the design theories discussed in section "Design Theories and Engineering Systems Design" fall into the abstract category of the aforementioned framework, and the process models to be discussed in this section fall into the procedural category, while the perspectives on design discussed in section "Perspectives on Designing for Engineering Systems" are relevant to all

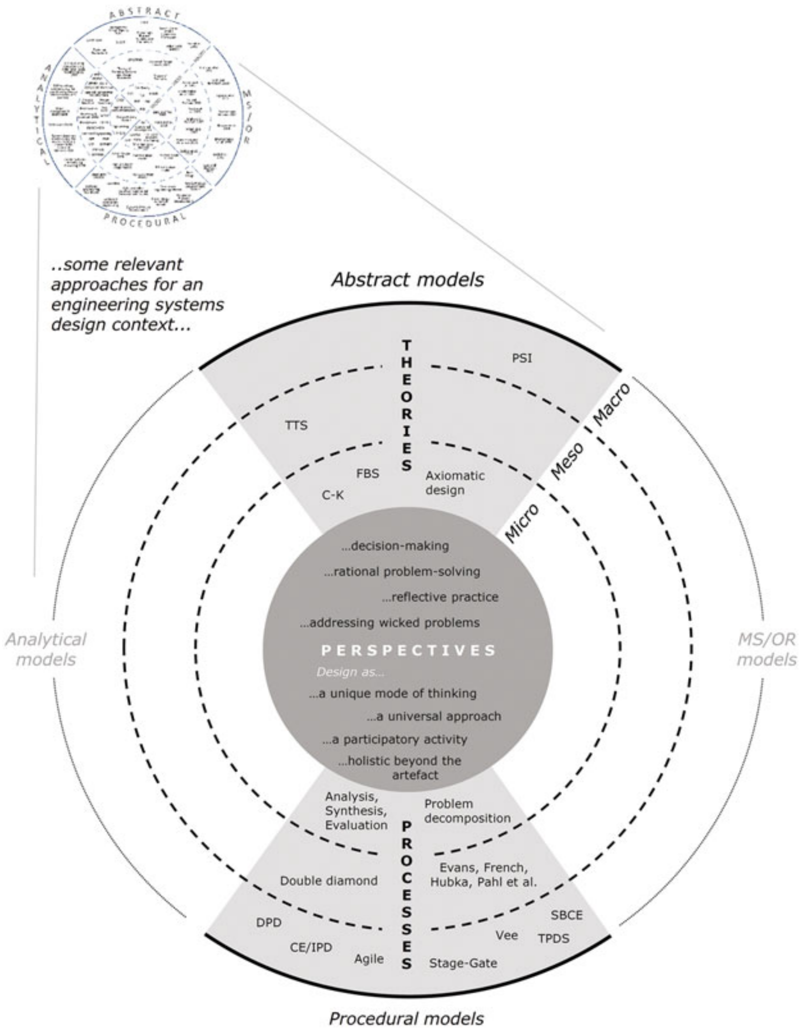


Fig. 7 Theories, perspectives, and processes on engineering systems design classified according to the framework of Wynn and Clarkson (2018). Each approach shown on the right-hand side is discussed in this chapter

types and scope of process model. The next subsections revisit some points from Wynn and Clarkson (2018) with consideration to the engineering systems design context.

Micro-level Procedural Design Process Models

Process models in this category capture overall strategies for design and design problem-solving. They often emphasise the iterative nature of design as well as the divergent/explorative nature of design that is articulated by Cross (1982), as described in the design perspectives subsection. These models apply to design activity on all of the subsystem, system, or system-of-systems levels articulated in Fig. 2.

A strategy that is commonly articulated in micro-level process models is that designers should follow a series of cycles, on each cycle working through the issues systematically and trying to avoid jumping to solutions based on their preconceptions. Evbuomwan et al. (1996) review work from the 1960s incorporating this recommendation, including Marples (1961), Jones (1963), and Archer (1965). Each of these authors recommends that design should follow the three main steps of analysis, synthesis, and evaluation. During analysis, the designer is expected to focus on a particular design subproblem and then work to structure it, yielding a set of objectives. During synthesis, they should generate multiple solutions. Evaluation involves the critical appraisal of those solutions against the objectives resulting from the first step, allowing the best design to be selected and yielding insight for iterative improvement. Design process models incorporating this strategy are often described as problem oriented because they stipulate starting from analysis of the problem to be solved on each design iteration (Wynn and Clarkson 2005). They suggest that within an iterative cycle, designers can formulate problem statements that do not presuppose a solution, which is desirable to help combine systematic reasoning with creative insights.

Another common recommendation is to begin by deliberately expanding the perceived boundaries of a design (sub)problem when it is encountered, e.g., by relaxing constraints, attempting to reframe the problem, or attempting to perceive it on a higher level of abstraction. This is conveyed, for example, by the well-known Design Council Double Diamond model of the design process (Design Council 2007). These recommendations have parallels in several of the design perspectives discussed earlier. It is thought that approaching a process in this way may help to remove unnecessary constraints and ensure that a broad range of potential solutions is considered.

A third common strategy is to decompose each encountered design problem into simpler subproblems with well-defined interactions as early as possible, such that the subproblems can be addressed individually prior to recombining solutions. As well as helping to make complex more problems manageable, this approach helps to divide work amongst team members (VDI2221 1987). Of course, the success of this strategy is highly dependent on how the problem is decomposed and how well the dependencies between its parts are managed during design.

Overall, the design strategies discussed in this paragraph are desirable and generally accepted as best practice but quite conceptual in nature such that practical implementation remains a challenge. Wynn and Clarkson (2018) write that they are for this reason often embedded in meso-level process models that are more concrete and specific for particular design tasks. Some examples of such models are described in the next subsections. Of all the design processes discussed in this section, micro-level process models are most similar to the design perspectives described earlier, and, as indicated, they directly embody parts of these perspectives as recommendations for practice. In contrast to design theories, their emphasis is on conveying accepted best practices for design rather than presenting unified, formal theories of what design involves.

Meso-Level Procedural Models

The micro-level models, as mentioned above, tend to be quite conceptual in nature. But many problems encountered during engineering systems design require resolution of specific technical issues. Meso-level design process models address this issue. These models essentially aim to support the generation of good designs in an effective and efficient manner by prescribing steps to be followed systematically. Some models of this type are very specific to a particular technical issue or company context. Others are more general in nature. With regard to the framework of Fig. 2, they are mainly focused on design problems appearing on systems or subsystem levels.

An early example of a meso-level process model is Evans' design spiral, which emphasises the iterative nature of the design process (Evans 1959). While his paper is focused on the specific issues of ship design, the form of the model depicts generally applicable insights about the process of addressing interdependent technical problems in engineering design. Noting that one of the most fundamental characteristics of design is the need to find trade-offs between interdependent factors, Evans argues that design cannot be achieved by following a sequential process alone. His model demonstrates how a structured iterative procedure is adopted to resolve such problems; early estimates are made and repeatedly refined as the design progresses, until the interdependent variables are consistent with each other. As the design moves forward, these design considerations are gradually refined by repeated attention until a solution that balances all of them is reached. At each iteration, the margins available to absorb changes decrease as the interdependencies are gradually resolved, smaller modifications are required, and higher-fidelity design and analysis tools may be applied to each problem. Evans notes that the effort required to progress the design, and the number of people that are involved, can often increase as the solution converges.

Other meso-level models present the engineering design process as a series of stages, each of which creates additional information to further concretise and detail the emerging design. In the mechanical design context, this stage-based form is exemplified in the early work of French (1999), originally published in 1971. Later models focusing on mechanical design, notably in the work of Hubka and Eder (2012) and Pahl et al. (2007), incorporate detailed lists of working steps to be followed to complete each stage. These models define how to create the specific forms of information that constitute a mechanical design, progressing from abstract to concrete so that each stage establishes the objectives and, also, the constraints for the next. These stage-based models typically show feedback loops between the stages. These indicate that design rework might occur at any point; they also indicate that learning can occur between projects and across product generations. In the mechanical design context, process models of this type are strongly influenced by theories of the information structures that define a mechanical systems design and its operation – such as the theory of technical systems (Hubka and Eder 1988, 2012) that was discussed in the Design Theories section of this chapter. Stage-based models also appear outside the mechanical design context.

Following stage-based process models is thought to have a variety of benefits. For example, Pahl et al. (2007) state that their model can help to avoid overlooking essential issues and tasks and might help to generate reusable design solutions. But these models have also attracted critique. For example, the models emphasise original design cascading from stakeholder needs (Weber 2014), while real-world projects often place strong limitations on the early concept design, with constraints such as existing product platforms and legislative requirements often predetermining the form of the solution (Pugh 1991). This is especially the case in the engineering systems design context. Considering coverage of the models, Gericke and Blessing (2011) argue that few models of this type integrate across engineering disciplines. Such integration is an essential issue in the engineering systems context. As an example, returning to the context of aircraft design, when designing the composite stiffeners in aircraft wings, the composite ply design requires the design of the structural properties and the manufacturing processes simultaneously. As the performance requirements increase, each component is required to realise several functions and the margins are reduced, which requires more design issues to be considered simultaneously by different domain experts. Such situations are typically not considered by the generic stage-based models discussed, although company-specific process models may capture how to perform these tasks while integrating the necessary disciplines.

Some researchers question whether it is realistic to expect a design project to follow a stage-based process. Whitney (2004), for instance, argues that the abstract-to-concrete ideal that is captured in these models must in practice be complemented by fitting together existing solutions, which is a bottom-up instead of top-down process. Konda et al. (1992) also point out that design process participants (especially from different disciplines) often need to negotiate to find a workable solution, which suggests a highly iterative process. These situations are especially relevant in the engineering systems design context.

Despite perceived limitations, the model forms outlined here have been widely adapted and applied. Stage-based forms, for example, may be found in many textbooks such as Ulrich and Eppinger (2015) and standards as well as in company practice. In the case of aircraft systems design, all major original equipment manufacturers, OEMs, use a design process in which the main design phases are clearly separated by design reviews followed by decisions. These processes are necessary to coordinate effort by many design teams and organisations. During the intense phases of a large aircraft development project, for example, several 100,000 s of drawings are produced on a monthly basis. Design is conducted in parallel, on different levels of the aircraft system. Since an aircraft is an integrated product, the behaviour of the system (aircraft) is effectively dependent on how well every component function by itself and how they succeed in working together. One challenge with such processes is the necessary focus on coordination, control, and management that follows with increased complexity, risk to hamper the efficiency as design processes. Hence there is need also for another level of processes, the macro-level processes, to help manage these issues.

Macro-Level Process Models

Moving onto macro-level process models, some concentrate on the large-scale organisation and management of design and development. Others consider interactions between the design and development process and the context into which the design will be delivered. Some are at a level of abstraction that could also be thought of as theories.

Considering the organisation and management of design on the large scale, one important challenge that companies face is to properly and efficiently integrate the systems, disciplines, tools, processes, and personnel working concurrently (Andreasen and Hein 2000). This is certainly the case in the engineering systems design context due to the high complexity and many interrelated design issues that must typically be considered. A number of process models address this context, that is typically referred to as concurrent engineering (CE) (e.g., Prasad 1996) or sometimes as integrated product development (IPD) (e.g., Andreasen and Hein 2000; Vajna and Burchardt 1998). According to Prasad (1996), CE emphasises approaches “to elicit the product developers, from the outset, to consider the ‘total job’ (including company’s support functions)”. Research in concurrent engineering has considered a broad range of topics including tools and processes to support collaboration, such as quality function deployment (Hauser and Clausing 1988); tools to manage information flow and design rework amongst concurrent work streams, such as the Design Structure Matrix (e.g., Eppinger et al. 1994); and design for X methods to help increase concurrency and information exchange especially in early design phases (Prasad 1996; Vajna and Burchardt 1998). Overall, while CE/IPD is thought to support integration and reduce late design changes (Prasad 1996), at the same time, increased concurrency between design work increases process complexity, increases the coordination burden, and can lead to increased rework during the design process.

Other processes in this category aim to mitigate the risk of costly iterations that cross stages of the development process. One such model commonly used in practice is the stage-gate process (Cooper 1990), which emphasises the use of formal, structured reviews to ensure a project has reached sufficient maturity before allowing it to proceed from one stage to the next. Another is the Systems Engineering Vee model which graphically depicts how a complex design is or should be decomposed into subsystems which are developed individually and then integrated, verified, and validated at each level as they are combined back up the hierarchy of subsystems (Forsberg et al. 2005; Gausemeier and Moehringer 2002). Key concerns in classical systems engineering include ensuring and documenting the definition, flowdown, and control of requirements and interface definitions, in order to avoid uncontrolled changes and the consequent rework. A third model that has gained attention is set-based concurrent engineering (SBCE), which advocates controlled reduction of technical uncertainties through a focus on up-front learning about whether the emerging design is feasible. The guiding principle is that concepts need to be proven feasible from the start to avoid large-scale rework and also to allow more standardised work later in the design process (Kennedy et al. 2014). SBCE proposes that this should be approached by developing and maintaining several workable designs for each subsystem and progressively discarding those options that are found to be infeasible or found to generate integration difficulties as the design moves forward. This is a significant departure from the more common practice of creating one design for each subsystem and iterating until they can all work together but, although offering many advantages, has proven challenging to implement in many contexts. SBCE also suggests that target specifications should, in the ideal case, be allowed to evolve within limits until it is established that the design will be able to meet them.

Authors have also considered how Lean models developed in manufacturing, involving concepts such as just in time and takt periods, can be applied to manage routine aspects of development processes (e.g., Oppenheim 2004). Other models look beyond workflow management and present lean methods, practices, and mindsets more holistically, such as the descriptions of the original Toyota Product Development System (e.g., Sobek et al. 1999; Liker and Morgan 2006), the learning first product development model of Kennedy (2008), and the Lean PPD model of Al-Ashaab et al. (2013).

The approaches discussed above focus on avoiding rework by establishing a funnelled structure to the design process. Decisions thought to have greatest consequence should be identified and resolved as early as possible, with efforts made to inform them as fully as possible. This overall strategy is visualised in the textbook model of Ulrich and Eppinger (2015). In contrast, agile models prescribe structured iterative cycles in which the design is regularly reintegrated as it progresses through increasing levels of definition and/or as more features are added (Cusumano and Selby 1997). This and other forms of iterative incremental development (IID) have been viewed as best practice in software development context for many years (see Larman and Basili 2003 for a review). Following the increasing amount of software design in many engineering systems, industries adopt agile (Beck et al. 2001) as a way of working based on its origin form the software development tradition. One of the attractions of agile is that it breaks down larger chunks of engineering activities to tasks that are treated in parallel in sprints, yet there are challenges for highly interconnected problems. They may be especially useful in contexts where customer needs and technology evolve rapidly, in cases where requirements are difficult to specify and where the emerging solution influences the nature of the problem. Considering similar issues, Ottosson (2004) developed dynamic product development (DPD), a model targeted at projects involving substantial innovation and creativity. Ottosson (2004) argues that the traditional emphasis on controlling projects by formal documentation and review leads to delayed information and reactive management. He also highlights the difficulty of long-term planning in a project involving uncertainty. To address these issues, DPD prescribes delegation of control allowing continuous managerial involvement at all levels, which is thought to facilitate real-time dynamic guidance. Furthermore, DPD aims to minimise loop-backs by allowing the concept to be adjusted continuously throughout a project, rather than freezing it early. A key consideration regarding application of dynamic, iteration-driven approaches such as IID and DPD to large projects is ensuring sufficient discipline and control of the development process (Turner 2007).

Section Summary

Design of engineering systems such as an aircraft in its interconnections with, e.g., airport services or air transportation regulations relies in many aspects on design processes as commonly represented in design process models. Micro-level processes and the practices they represent instruct designers to approach design in a way that helps to avoid, e.g., jumping to suboptimal solutions and attacking problems in an inappropriate sequence, both of which might lead to poor solutions and to design rework.

Meso-level processes capture and communicate a shared understanding of central concepts, e.g., how design solutions are matured through the activities undertaken and when particular reviews should take place. Continuing on the requirements example, meso-level processes are helpful when organising and decomposing the requirements phrased using microlevel processes.

As was indicated at the start of this chapter, engineering systems design typically involves many people and many organisations requiring careful coordination to converge to a consistent result. Macro-level processes provide overall approaches to frame and bound a large scape problem and facilitate both creative, synthesis activities to utilise new technologies, possibly from new domains into the process. By helping to coordinate the people and activities involved in design on a large scale, macro-level processes can be useful to reduce wasted effort in the design process and allow designers to focus effort and time on the development of robust and resilient engineering systems.

The engineering design communities are increasingly emphasising the role of systems of systems, but theoretical foundations are not yet well established (Subrahmanian et al. 2020). This also depends on the audience of the processes. The macro- and meso-level models included above focus on addressing engineers and designers.

Application of Design Perspectives, Theories, and Processes to Practical Case Examples

Engineering design can be conceptualised in many ways. While the perspectives, theories, and processes discussed in this chapter are each more suitable to some design situations than to others, most are intended to be general to some degree. They generally do not provide straightforward algorithms or checklists for solving design problems – rather they help designers develop insight, and they suggest ways to approach such problems in ways that have evidently been successful by others.

As already discussed, engineering systems design is rarely done by a single individual. The common situation is for one or several teams to coordinate their efforts in projects. The necessary collaboration and coordination can benefit from methods and processes to support convergence and ensure quality of the work. One of the important roles of perspectives, theories, and processes is in providing a common set of terms and work principles that a team can come together on and collectively adapt to their own needs. In fact, some of the problems that can be observed in practice arise from divergent interpretation of concepts. Design perspectives, theories, and processes provide comprehensively researched concepts that can be implemented into company-specific instructions and models and as guides (templates) for authors of these instructions and models.

The different perspectives on design help designers to appreciate particular aspects of design, as depicted in Fig. 3. Any complex design situation involves a multitude of challenges that need to be addressed, and selecting appropriate perspectives for the given situation can help to find appropriate methodological support. For example, airport and aircraft design, which this section uses to explain how design relates to different dimensions in engineering systems design, are prime examples of wicked problems (see section "Design as Addressing Wicked Problems"), and hence approaches to support such problems are relevant.

Figure 8 builds further on Fig. 2 to illustrate that engineering systems design is subject to many challenges arising from the systems complexity itself (large aircrafts have millions of parts and millions of lines of software code) and the long and varied use of the product but also the organisational and societal context in which the products need to operate. Intervening in such systems necessitates that designers address design problems across multiple dimensions. De Weck et al. (2011) provide a set of engineering systems terms and definitions that can serve as a guide to many of the relevant topics. In the following, we briefly discuss a subset of the dimensions depicted in Fig. 8, which will help illustrate the role perspective, theories, and processes can play in engineering systems design practice.

Firstly, as already stated, for each intervention into a complex engineering system, the designers face a number of challenges and need to operate on multiple dimensions. The colour scheme of Fig. 8 reflects the three main dimensions of the PSI framework discussed earlier (Reich and Subrahmanian 2020). In particular, the blue dimensions relate to what is being designed, the green dimensions relate to the stakeholders in design, and the orange dimension relates to the institutional aspects, i.e., the economic, managerial, organisational, and political aspects

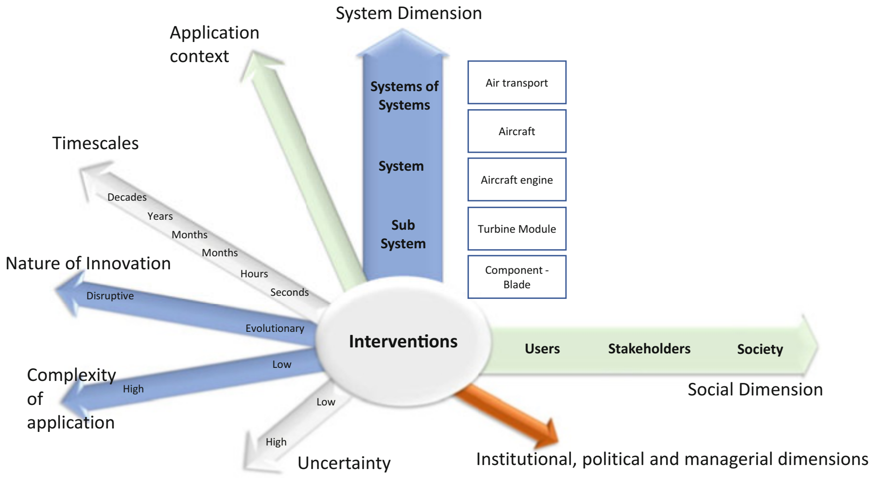


Fig. 8 Some aspects that bring challenges to engineering systems design

impacting design. As pointed out in the earlier section, engineering design theories, perspectives, and processes have traditionally paid little attention to the institutional space. The addressing of this gap is a current trend in design theory development.

Secondly, elements of the aircraft system have very *different timescales*. An aircraft is in development for typically a decade and produced, used, and upgraded for many more decades. As such, the structural basis of the actual mechanical solution may withstand several decades in service, while much of the other equipment in an aircraft has a shorter time in service. Electronics and software need to be replaced and upgraded with a cycle of months or a few years. Adding to the time dimension is the rate of change is the air transport system, where technologies, systems, and fuels but also societal rules regulating flight operation may change many times. Customer preferences and the role of the aircraft can change in a way that the original intent and design prerequisites become invalid.

Thirdly, the *nature of innovation* plays a decisive role for selecting suitable design approaches. Disruptive system innovation, such as aerospace replacing energy transformation principles (electrification, hydrogen power, hybrid technologies), is significantly different from evolutionary development. Simply comparing different types of solutions may be difficult unless system-level performance, behaviour, and functionality can be compared on equal bases. Here, design theories such as axiomatic design (Suh 1990), C-K theory (Hatchuel and Weil 2009), or FBS (Gero 1990) provide frameworks to compare disparate solutions. In addition, disruptive innovation of entire systems requires multiple systems and people to change their way of interacting with the systems. Design thinking perspectives have been found useful to improve communication between different types of competences and stakeholders and promote ideation.

Fourthly, the *application context* of engineering systems design accounts for the situations the system is being designed for. Perspectives, theories, and processes need to be adapted to the particular situation or context. Generic and typically abstract design theories can be useful to design health systems, aerospace systems, communication systems, and more, yet the contextual terminology, the technologies used to design and realise the systems, the material, and so forth are different. There are few recipes to be found in design theories and perspectives, but there are many valuable insights on how to make the systems "designable". Design theories origin from one domain, e.g., software, and are at present influencing design of multi-technological systems, such as the agile manifesto. Also here, agile principles need to be adapted to the particular challenges for the new context.

For example, this illustrates the interplay between the functions that a system needs to carry out and the structure that it has. A large existing structure might have to carry out new functions or a changed structure needs to maintain existing functions. To analyse this, theories discussed in section "Theory Meeting the Challenges of Design", such as FBS (Gero and Kannengiesser 2004), might provide conceptual clarity between the purpose of the system (function), the elements that it has (structure), and the resulting behaviour. Social changes and situations, such as the COVID-19 crisis, completely altered conditions for flight transport systems. The ability to adapt and design for the unexpected has a big impact, where designers may benefit from building on modular systems, where design theory provides a means to decompose and organise complex systems. For example, axiomatic design (Suh 2001) advocates a clear mapping between components and functions, so that if one function changes, others remain relatively unaffected.

Fifthly, a related dimension is that of *Uncertainty*. Design by definition is done in advance of the realisation of the systems and products. At the start of a design initiative, typically both the knowledge of the use conditions and the forthcoming design solutions are vague, incomplete, and imprecise. Both design theories and processes have been developed partially with the objective of reducing the uncertainty of designs by seeking knowledge that allows uncertainty to reduce. The concept of wicked problems by Rittel et al. (1973) (see section "Design as Addressing Wicked Problems") is a good source of inspiration. As designs mature, increased use of engineering modelling and simulation as well as prototyping can be effective. Many uncertainties arise because the use context has not been well understood and explored, which can potentially be alleviated through participatory design approaches (see section "Design as a Participatory Activity").

Sixthly, in terms of *system dimensions*, elements of engineering systems are often highly optimised technical systems, such as subsystems of aircraft. The overall design problem is decomposed into smaller and more manageable problems (see section "Design as Rational Problem-Solving"). Even though the problems cannot be fully decomposed in theory, they have to be decomposed and integrated later in practice to manage division of labour between different designers and make the tasks of an individual more manageable. This applies in particular to engineering systems design which typically addresses large problems at multiple levels of hierarchy, as suggested by Fig. 1. In this decomposition, some design theories and processes might be more applicable than others to particular aspects of the design. For example, aircraft designers might take a participatory approach (see section "Design as a Participatory Activity") to designing the overhead luggage bins, because the passengers have to use them as quickly and smoothly as possible, but the users of the aircraft are not particularly relevant to the design of the hydraulic system. The hydraulic system can be treated using mathematical decision-based methods (see section "Design as Decision-Making"). A technical system cannot be designed in the absence of understanding and to some extent designing the processes and products it needs to interact with, so that PSS approaches (section "Design as a Holistic Activity Beyond the Artefact") might be useful.

Processes capture the experiences required to systematically bring a project to a successful conclusion. Engineering design focuses on the process of finding and defining products in response to needs or opportunities in an effective manner. The processes of design in context of an engineering system can also be looked at and described from many different angles. Some stakeholders such as airport providers might also be interested in the macro view of the product development process, because they need to understand what interfaces they need to provide and when relevant information is available. On the other hand, particular engineering teams are interested in a detailed activity perspective.

To summarise, the above discussion suggests how some of the theories, processes, and perspectives discussed in this chapter could be used to address some of the challenges of engineering systems design. What is appropriate depends on the specific situation.

Conclusions

This chapter has unveiled a selection of well-established design perspectives, theories, and processes that are applicable when designing engineering systems. Multiple theories, perspectives, and processes can coexist with equal validity. They help designers to understand and address design problems, building on different approaches. What is most helpful depends also on the situation at hand.

The multifaceted nature of design allows for a range of useful perspectives on design (discussed in section "Theoretical Perspectives on Design") that help engineering system developers to address problems encountered in their work. For instance, in situations where they need to organise their complex, typically wicked (Rittel and Webber 1973) problems, Simon (1996) discusses how to carve out more concrete problem definitions using the perspective of bounded rationality, and Schön (Schön and Wiggins 1992) elaborated further on cycling between the abstract and concrete as a means to progress in design. To think and act as a designer has become the cornerstone for approaches that have become popular as universal problem-solving activities – typically engaging a team of diverse skills in seeking solutions. At present, thought leaders in design research seek to develop design perspectives that extend way beyond artefacts and concrete systems to incorporate issues relevant to the larger-scale socio-technical engineering systems context. As such, these perspectives of design help to nuance and view seemingly overwhelming problems in new light.

Formal theories of design (as discussed in section "Theoretical Perspectives on Design") have greater ambition on formalism and seek to understand design and, in some cases, aim to robustly predict the outcome of design activities. Early theories assumed a well-defined problem and started with the artefact being designed, such as theory of technical systems Hubka and Eder (1988) or Andreasen (1980), while others take a more abstract view on design, such as Suh (1990) with axiomatic design, Gero and Kannengiesser (2004) with their FBS ontology and framework, and Hatchuel and Weil (2009) with their C-K theory. Current theoretical developments seek to take a wider systemic view of design (Subrahmanian et al. 2020). There is a trade-off between general applicability of theories and the effort required to adapt them to a particular context.

Perhaps more widely applied are the processes (as discussed in section "Design Processes") that offer concrete design steps and sequences such as Pahl et al. (2007) or Ulrich and Eppinger (2015), while other processes offer high-level frameworks to help manage complex design projects. Examples of the latter are concurrent engineering (e.g., Prasad 1996), the Toyota System (e.g., Liker and Morgan 2006), or the agile manifesto (Beck et al. 2001) and their derivatives. These are highly relevant to engineering systems designers due to the approaches' proven utility for large-scale and complex problems. One of their drawbacks is that (in common with design perspectives and theories) they need to be adapted to each specific context.

Design theories and design processes that have been tested and validated through research can be of great value when addressing complex problems for engineering systems design. Many of the problems that frequently appear in development situations can be viewed as design problems, whether they relate to formulating the problem in a way that they can be solved or determining how to evaluate whether a proposed solution actually meets expectations and requirements. Design theories have evolved over decades of practical development and bring well-structured approaches to help in addressing complex problems. They are well worth the investment of time and effort to appreciate them! In doing so, it is essential to recognise that design has simultaneously a technical dimension and a social dimension, including human, institutional, and political factors affecting the decision-making process. For the engineering systems addressed in this book, successful design needs to acknowledge both factors in a balanced way, where a balance between rationality and situation awareness for decision-making needs to be attended to.

Cross-References

▶ Architecting Engineering Systems: Designing Critical Interfaces
▶ Asking Effective Questions: Awareness of Bias in Designerly Thinking
▶ Designing for Technical Behaviour
▶ Engineering Systems Design Goals and Stakeholder Needs
▶ History of Engineering Systems Design Research and Practice

► Roles and Skills of Engineering Systems Designers
► Systems Thinking: Practical Insights on Systems-Led Design in Socio-Technical Engineering Systems

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The Evolution of Complex Engineering Systems

4

Claudia Eckert and John Clarkson

Contents

Abstract

Engineering systems are rarely designed from scratch. They are socio-technical engineering systems that evolve over generations of products and policies. This chapter uses tram transportation to illustrate how engineering systems evolve over many decades. A brief comparison between trams in the UK and Germany

C. Eckert (✉)
School of Engineering and Innovation, The Open University, Milton Keynes, UK
e-mail: claudia.eckert@open.ac.uk

J. Clarkson
Department of Engineering, University of Cambridge, Cambridge, UK
e-mail: pjc10@cam.ac.uk

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illustrates that systems that are at one point very similar can develop in very different ways due to seemingly innocuous decisions. The evolution of systems is explained in terms of two concepts, *path dependency*, which explains how future designs are restricted by decisions taken in the past, and *engineering change*, which handles the effects of a change on parts of the system and neighbouring systems. To understand the impact of change, it is important to model and understand how different elements of a system are connected and how well a system meets its requirements to identify those elements of a system that can accommodate new demands. Different approaches have been developed to manage and predict engineering changes. Understanding and managing change is particularly important for complex engineering systems, which often constitute large-scale long-term investments and are expected to keep operating while the changes are carried out. This chapter concludes with a discussion of how systems can become more resilient to change either by becoming able to absorb expected changes or becoming more flexible in adapting to change.

Keywords

Change propagation · Dependency modelling · Design for flexibility · Engineering change · Engineering systems · System evolution · Transportation

Introduction

Complex socio-technical engineering systems are rarely designed from scratch to remain unchanged over their entire lifecycle but most rather evolve over many years. They are altered and upgraded, parts might be removed or people might transition, and other parts are added and behaviours and policies change. In designing and managing such engineering systems, it is important to understand the changes that they have already been subject to and to think of the changes that might be coming. Making changes to a working system is far from trivial – by touching one subsystem, many others might be affected, and the costs of any change can spiral out of control very quickly. New elements are added to systems that could not have been conceived from the outset, and different systems become connected that have originally been thought of as separate. In this sense, complex socio-technical systems may be thought of as partially designed and partially evolved (de Weck et al. 2011). For example, road systems were set up long before the car was invented and now have to accommodate multiple, different means of transport, alongside the impact of changing attitudes to automotive travel and levels of intra- and inter-vehicular automation.

The evolution of complex socio-technical systems is hard to predict, not only because of evolving technology and the decisions that designers are taking but also because of external influences. As society changes, user preferences and desires change. Political changes also lead to changing funding priorities, research funding levels, or subsidies. Therefore, systems that may look similar in their conception can evolve in many different ways.

The engineers working on these systems know that it can be difficult to develop an overview of the whole system, anticipate which systems might be affected by a change, and take actions to limit the uncertainty arising from within their own organisation. However, many factors affecting complex socio-technical engineering systems are beyond their control. This chapter uses the rise and fall, and slow rebirth, of the UK tram system as an illustration of the evolution of a complex socio-technical system and the factors that affect it and are affected by it. This example illustrates how decisions about elements of the system can have long-term effects on the whole and, at the same time, how complex socio-technical systems can be affected by global and social trends where what seems like a short-term opportunity can have a long-term detrimental effect on the whole system. Contrasting the British tram system with the German system further illustrates how, from similar starting points, different systems can arise.

Over the years, several tools and methods have been developed that help build understanding of the connectivity within a system and in anticipating and mitigating against the effects of changes. In addition, a number of such methods have been specifically designed to map connectivity and predict the effect of changes. These methods and tools can be used in the design of socio-technical engineering systems to support the design decisions that are necessary to make such systems more resilient to change. The term resilience was originally used by Holling (1973) in the 1970s to describe "the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables" and later applied to different types of systems to mean "the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions" (UN 2009). The US National Academy of Science succinctly stated that resilience is "the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events" (NRC 2012, p. 1). For engineering system, Hollnagel et al. (2006) narrowed this to "the ability to adjust its functioning prior to, during, or following changes, disturbances, and opportunities, and thereby sustain required operations under both expected and unexpected conditions". Engineering systems also need to be flexible to accommodate changes, either by responding to new requirements as they are or by designing the systems in the first place to be easily changeable.

At the same time, the language of systems design has evolved, from its origins in complex technical systems, to become more sophisticated and to include humans and human behaviour as key elements within the description of the system, while the language of product and service design has generally been more inclusive and relevant to socio-technical systems. Consequently, many of the references in this chapter that come from the world of product and service design can be interpreted, with the replacement of the word "product" by "system", as pertinent to a discussion on the evolution of socio-technical engineering systems.

How complex systems evolve and prosper is often down to policy and the decisions that policy makers take. This is illustrated in this chapter by the different fates of tram systems in the UK and Germany. Both were prospering before the First World War, but while the British systems largely declined without active policy support, the German systems have been expanded to provide sustainable mass transport. Policy set the constraints and the requirements under which the systems operate. Complex systems depend on the interplay between technology and policy, which can direct technology through research funding, subsidies, and investment.

In summary, this chapter looks at the design and evolution of complex socio-technical engineering systems. Section "The Evolving Tram System" sets the context through a brief description of the evolution of tram systems in different parts of Europe which from very similar beginnings in the late nineteenth century diverged greatly after the Second World War. This demonstrates the impact policy approaches and constraints can have on large systems. Section "Complex Interconnected Socio-Technical Engineering Systems Changing over Time" discusses how socio-technical engineering systems change over time and points to the causes of change and the processes by which changes are carried out. The challenge lies in predicting how a change might propagate before embarking on it. Different approaches to make systems more resilient are discussed in section "The Design of Resilient Systems".

The Evolving Tram System

Infrastructures are systems that organise and manage complex systems of flows, movement, and exchange (Allen 1999). They usually consist of heterogeneous elements and support multiple different stakeholders, such as the transport system and the energy supply system. In this section, we discuss tram systems as an example of an infrastructure that evolves over time. Different infrastructures are often interconnected and are increasingly becoming more connected (Saidi et al. 2018). For example, tram systems are connected to other forms of public and private transport as well as electricity supply systems.

Before there was a public transport system, people either had to walk, ride a horse or donkey, use a cart, or simply stay put. During the nineteenth century, horse-drawn tram or light rail systems started to be set up all over the world and flourish, right up to the First World War. After the war, a number of the tram systems were augmented by buses that offered greater flexibility, while in many places they were pushed out by the buses. While many cities, in particular in Central Europe, have maintained and extended flourishing tram systems, other cities, for example, in the UK and France, have invested vast sums to reintroduce lost trams.

Tram and light railway systems are cheaper to install than heavy train systems as they are powered by electricity and produce less emissions than buses powered by internal combustion engines. This is a huge advantage in already polluted city centers, and they are comparable in emissions to guided buses (Hodgson et al. 2013). Trams also have typically higher capacity and can run more frequently than buses along the same lines. However, setting up a tram system is an expensive, very long-term investment as the tracks and the power supply need to be put in place and the traffic rearranged in such a way that the trams can run smoothly alongside conventional traffic. This typically requires dedicated tram lanes or rerouting through traffic away from tramlines, and in pedestrian areas, safety becomes a particularly important issue. Such decisions leave a lasting legacy that can constrain further development, and, as a result, some authorities have many years later moved their tramlines underground in city centers, entailing many years of disruption.

New alternatives to tracked trams are beginning to emerge, as some cities have introduced guided buses which offer the flexibility of new services and routes but are still largely run on internal combustion engines. Other cities have fleets of natural gas or electric powered buses, some of which are charged by induction at bus stations. In China, new hybrid bus/tram systems are appearing, where trams on wheels are powered by inductively charged batteries and guided by GPS systems. These have the feel of a tram to the user but do not require the investment of a permanently fixed infrastructure.

The initial purchase price of trams, ranging between 1.5 and four million euros, is much higher than the equivalent cost of buses (Hodgson et al. 2013). However, the expected live time of the tram, with suitable refurbishment, can run from 30 to 50 years, compared to 8 to 10 years for a bus, and it is able to carry a much larger number of passengers.

Trams in the UK: Decline through Underinvestment

Most cities in the UK had flourishing tram systems at the turn of the twentieth century. Today only eight towns in the UK have trams. Of these, only Blackpool (Fig. 1) managed to maintain a continuous tram service throughout the twentieth century, and the other seven systems have been more recently rebuilt at huge cost

Fig. 1 Examples of Blackpool trams (by Pauline Eccles, CC BY-SA 2.0, https://commons.wikimedia.org/w/index.php?curid=19281174; Jon Bennett – Crich Tramway Museum ExtravaganzaUploaded by oxyman, CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=9522468)

and with much reduced coverage compared to the predecessor systems. They are operated by private operators. For example, the Edinburgh tram system was reopened in 2014 at a cost over £¾ billion pounds for a 14-kilometre line, after the previous much larger system was shut down in 1956 (Edinburgh Tram 2021).

What had happened? The tram systems were very well maintained before First World War. After the war, numerous military trucks were decommissioned and were purchased by cities as cheap means of transport. Buses soon became the vehicle of choice and the tram systems were typically not expanded. The tram infrastructure began to wear out in the late 1920s and 1930s, when cities that needed to deal with the aftermath of the great depression had no money to invest in significant maintenance and upgrades. This defined a tipping point, and the systems that were left were patched up and kept running until after the Second World War, when most cities moved over to buses, to avoid major investment both in tracks and in rolling stock, and car ownership began to increase rapidly. However, people liked travelling on trams, and when they were replaced by buses, the use of public transport dropped significantly (see Costa and Fernandes 2012, for a history of technology diffusion and market organisation in European urban public transport).

Trams in Germany

Most German cities now have extensive tram systems. Like the UK cities, the tram systems largely originate from the nineteenth century and have been supplemented with the addition of bus lines between the two world wars. However, in contrast to the UK, many of the systems were upgraded and longer and more comfortable trams were introduced. During the Second World War, many tram systems were damaged but were patched up to get public transport running again as soon as possible post was when very few private vehicles were available and fuel was scarce.

New rolling stock, produced in Germany, was purchased in the late 1940s and 1950s, and German cities saw trams as a way of combatting traffic congestion and pollution in the 1960s and 1970s. Most transport systems are fully or partially owned by the cities as part of their utilities, which also run their water, electricity, and gas provision. As the cities took a long-term strategic view on transport, many increased the tram network and redesigned the road system to minimise disruption caused by trams sharing the same space as cars (e.g., Doll and Listl 2007). Public transport was coordinated at central exchanges, and in the 1990s, the frequency of trams was increased.

How the service is operated also has a profound effect on how it is used. In early trams, it was customary to jump onto the moving trams, which is difficult in a floor length dress. In Germany, woman used trams more when fixed tram stops where introduced (Schmucki 2002). The introduction of more frequent and coordinated services also increased the uptake. The transport systems also offer numerous monthly and yearly ticket schemes, to encourage as many citizens as possible to use public transport, at reasonable cost, through large transport zones which often include local rail services offered by the state rail company. Combined monthly tickets for trams, buses, e-bikes, and car-share cars are also offered to enable door to door transport as a means to reduce car ownership and use while maintaining the flexibility of private car ownership.

A Comparison of Approaches

From a similar starting point, the tram systems in the UK and Germany evolved in very different ways. Both countries had a variety of manufacturers of trams, several of whom also supplied the aerospace industry during the Second Would War. One of the major German tram manufacturers is Siemens, who was also a pioneer of electric trams. Between the wars, the UK has a preference for double-decker trams, which, like modern double-decker buses, require climbing up a narrow winding staircase to reach the upper level.

Both countries had good coverage by tram networks in major cities before the First World War, and, between the wars, as the German tram networks grew, the UK public transport largely expanded through the use of buses. Investment in infrastructure was a major issue in both countries in the first half of the twentieth century, when little money was available for the substantial upgrade or maintenance of infrastructure. In response, the UK opted for buses, which require less upfront investment, while Germany did not have the money to invest in fleets of buses and had to patch up the tram systems to keep people moving.

One key difference lies in the ownership of public transport. In the UK, the transport systems are largely run by the city councils as an isolated concern or by private companies where success of individual lines is based on whether they are likely to make a profit. As a result, public transport in rural areas and parts of suburbia is often limited, so that buses are used by people who have little alternative, i.e., the young, the old, and the poor. This causes a vicious circle of increasing car traffic in many cities, particularly in the absence of investment in cycling infrastructure, which they then attempt to manage through measures such as congestion charges or increased parking fees. In consequence, rather than relying on public transport provision, schools are setting up their own bus routes through private companies to transport their students to school. In Germany, they belong to joined-up public utilities, who can take a long-term and holistic view of running the city. Public transport policy is then seen in conjunction with traffic planning, with the aim of reducing car travel into the city centre, and road systems are planned to disentangle car and tram routes, by building bypasses or blocking through traffic for cars in pedestrian areas. Trams are also seen as effective ways to reinvigorate and develop parts of cities.

A further difference lies in ticketing. Bus travel in the UK is expensive, so that for a family of 4, it is often cheaper to take a taxi, or drive and pay for parking, than it is to take a bus. By contrast, in Germany, there are monthly ticket options and offers in most cities, along with highly reduced tickets for students, which can be used for different modes of transport within predefined areas.

Both tram systems started with similar physical infrastructure and rolling stock but diverged because of different investment decisions and incentives to use the systems. Neither technical excellence nor need are guarantors for the success of the system, but rather the systems need to evolve with the needs of the population. Wrong decisions are difficult and costly to undo. Decisions have long-terms effects, which only show up many years later as the effects of the underinvestment in the UK show. Complex socio-technical systems are subject to path dependency, which as the next section will explain in more detail, means that they cannot escape the decisions taken in the past. This long-term resilience is not only the response to technological advances but also to consistent policy.

Characteristics of Complex Socio-Technical Engineering Systems

The example of tram systems brings out several general characteristics that are important in the design and evolution of complex socio-technical engineering systems. Like the tram systems, complex socio-technical engineering systems are often evolutionary, developing over many product generations with change dependent on new requirements and the specific state of the system at any particular point in time (Basalla 1988; Malerba 2007). For example, in some cases it is possible to patch up tram tracks, whereas in other cases they have to be replaced, requiring higher investment and, perhaps more importantly, disruption of service. It is also a matter of timely intervention, where early intervention can save much higher costs later (e.g., patching up vs. replacement), and yet a request for intervention too early may result in the money not being released.

Some tram systems are now well over 100 years old. Complex socio-technical engineering systems require a long-term view, where interventions need to be planned in a way that does not inconvenience the users and does not require too much investment at any one time. A key factor in the decline of the UK tram systems was that the majority were built roughly at the same time at the end of the nineteenth century and needed similar upgrades at the same time. Limited cash then condemned many systems to the scrap yard. Perversely, restarting a system that has been stopped can be more expensive than maintaining a system through time and potentially be even more expensive than building a new system from scratch, as shown by the example of the reintroduction of trams in Edinburgh.

Tram system is connected to the bus system and to other kinds of transport, such as cars, bicycles, and trains. This interconnection with other systems needs to be considered in the design and evolution of complex systems. Depending on what is considered to be within the scope of consideration, different decisions are made. For example, in Germany the trams have long been seen as part of a unified transport solution. So far modelling efforts have concentrated on short-term operational purposes and extreme events; however, as Saidi et al. (2018) point out, the long-term effect of future policies and scenarios requires more research.

Over time the systems evolve. Changes are often triggered by real problems with the system, where repeated problems and user discontent can lead to improvements and changes and where milder long-term irritations might not. Getting tram systems to be effective requires a large-scale disentanglement of car traffic and tram traffic, an investment that was in part triggered by discontented car drivers.

Changes to a system can have effects that are not necessarily anticipated when the changes are planned. It is these knock-on effects and associated disruption to the system dynamics that make changes to complex socio-technical engineering systems potentially extremely expensive. For example, changes to public transport have effects on parking, road use, etc., which in turn affect the businesses and people who live on these streets.

The success of the systems does not only depend on their functionalities but also services they offer or are part of. Many complex socio-technical engineering systems are in fact product-service systems (see Mont 2002), where it is important to think about the service that is being provided by the system as a whole. Service design has stressed in the last 20 years the importance of engaging with users their values (Yu and Sangiorgi 2018). This came too late for the original UK tram system but plays a huge role in its uptake in Germany. Frequent trams and convenient ticketing may increase the uptake of systems. However, this is only possible if the system has the capacity to accommodate changes to the service. Trams can run more frequently than buses, but cities also need to be willing to invest in more rolling stock and infrastructure, such as bridges or stops to be able to absorb the added volume of traffic. This means that systems need to be designed with a certain degree of slack or overdesign to begin with. However, a system that has been overdesigned is not necessarily optimised to meet the immediate requirements, and it is then tempting to eliminate the overdesign. For example, by taking out non-profitable tramlines, in the long run, this could prove more expensive when lines need to be reinstated. Nonetheless, many systems are overdesigned to accommodate peak demands. For example, transport systems have to cope with end-of-school or football matches. The more the operators know about these events, the better they can manage them. Then an upgrade to the system might not be required if different mitigating measures can be found, such as buses at school closure time.

Over the years, systems go through good times and bad times and still need to keep functioning. A resilient system (see section "The Design of Resilient Systems") needs to be able to handle unexpected and uncertain events, but it also needs to do so without incurring unreasonable costs. A resilient system can also harbour the danger that the operators become complacent and do not invest in the upkeep and renovation of their system. In the 1930s, the UK tram system should have been upgraded, but the system was sufficiently resilient to keep going until it was finally worn out in the 1940s and 1950s.

This implies to a number of characteristics of complex socio-technical engineering systems focused around concepts of change:

- They are highly interconnected internally and externally, exhibit predictable and unpredictable emergent behaviours, and are dynamically changing over time.
- They benefit from long-term planning and timely scheduling to facilitate essential and multiple changes through an extended lifecycle.

- Their boundaries are important in defining the scope of interest, including material and seemingly immaterial elements, and may be determined by external factors.
- Their resilience is dependent on defining sufficient margins and potential for adaptability to handle future changes in performance, demand, and service.

The remainder of this chapter will address these issues through discussion of complex interconnected socio-technical engineering systems changing over time, change propagation, and the design of resilient systems.

Complex Interconnected Socio-Technical Engineering Systems Changing over Time

As the example of the tram systems illustrates, complex socio-technical engineering systems are rarely designed from scratch but evolve over many years. Even new systems, like the current generation of the UK tram system, take many years to build and the new lines that are added are constrained by the lines that were built first. In this section, we will talk about the concept of path dependency, which explains how long-lasting systems are influenced by earlier decisions which are often long forgotten. For example, tramlines have been designed to bring employees to factories that have long disappeared.

The overwhelming majority of products and systems are designed as a modification of previous systems and products. The tram systems have evolved over time, and the bus system that replaced them was also based on the existing tram systems. The designs of the trams themselves evolved over the years, where major parts of the design of a product generation are carried over to the next (Fig. 2). Both the design of a new generation and the modification of the design due to new requirements during the design process are part of process of engineering change. The more interconnected a system is, the more change propagation is an issue. It is therefore

Fig. 2 Different product generations of trams (by Deltastrahlung – Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=33787884)

important to understand and to model the connectivity in system to be able to predict and anticipate the effects that changes will have. In the chapter, we will focus on research from engineering design and project management, so that our examples are drawn from the design of complex products. The same logic of interconnection applies to changes in non-physical systems; however, this has been much less researched.

Engineering change and its management is inexorably linked to the concept of continuous system improvement (Boznak and Decker 1993). Companies see engineering change often as a burden, not only if changes arise from mistakes, but also as an opportunity to improve the systems (Acar et al. 1998). However, engineering can also cause disruption to supply chains and manufacturing processes and cause waste, as parts can no longer be used (Brown 2006).

Throughout this and the following section, we will introduce concepts, largely from engineering design, and illustrate them with the tram system introduced in the previous section.

Path Dependence

The "QUERTY" standard, adopted by the vast majority of typewriters and computer keyboards, is not the most efficient of layouts for fast typing (Norman 1990) but is widely acknowledged as that chosen to avoid jamming on early mechanical typewriters. Its persistence to the present day has more to do with its early adoption, which encouraged familiarity with the layout and investment by office managers, than the fact that you can spell TYPEWRITER only using the uppermost line of letter keys. Similarly, the adoption of the 4 feet 8.5 inch railway gauge by over half of the world's railways, despite being narrower than the optimum, is the direct result of its use by Robert Stephenson in early mining tramways (Puffert 2002). Both these examples illustrate the phenomenon of path dependency – the dependency of outcomes on the path of previous outcomes, rather than simply on current conditions.

Economists have picked up on the concept of path dependence to explain increasing returns. As technology is taken up, its cost goes down, which leads to further uptake and the development of coevolving products and infrastructures. This in turn makes other technologies uncompetitive and shapes customers' expectations (Pierson 2000). The result can be that society gets locked into particular solutions (Unruh 2000). This is particularly an issue for large-scale infrastructure systems; for example, Gross and Hanna (2019) explain how the UK has been locked into natural gas for domestic heating and point out the challenge for policy maker to create incentives for low carbon technology that can break the dominance of natural gas. However, it is not only products or physical system that can suffer from path dependency but also organisation that gets locked into a structure of organisation and the mode of decision-making (Greener 2002).

Path dependency can have a significant effect of the development of complex systems, but does not imply that only single solutions to known challenges exist but rather that particular solutions may exist and persist in different ecosystems. For example, most jet engine manufacturers use a simple two-spool (shaft) design even though this compromises engine efficiency, while Rolls Royce adopted a more complex and heavier three-spool design in the RB211 and later Trent series engines to improve their inherent efficiency. In both cases, the investment in one or other of the architectures, a decision taken at a particular point in time, resulted in a “lock-in” to the chosen approach (Liebowitz and Margolis 1995). This situation persisted until only very recently when Pratt and Whitney introduced a gearbox to their two-spool architecture to improve the efficiency of their latest high bypass ratio engine, a decision forced by the properties of such a configuration and enabled by technological advances with gearbox design; their reluctance to make such a change is being driven more by technological and cost constraints than by fixation with the two-spool design.

Path dependency can arise as the direct result of significant capital investment in a particular solution, where the ongoing running costs are far lower than the cost of replacement. For example, many cities have tram systems that reflect the traffic flow of 100 years ago. It can also be the result of technical relatedness, where the convenience of replacing some elements of a system as like-for-like enables ongoing upgrades at the cost of solutions for related elements persisting beyond the life of any individual equipment. The gauges of the trams have linked the design of trams over most of their history. Persistence may also be the result of increasing returns from use, a common benefit arising from an emerging standard (David 1985, 1987). This latter driver of path dependency was further explored by Arthur (1989) who proposed that a series of small decisions, or events, might result in positive feedback, reinforcing the value and subsequent adoption of the chosen approach. Trams have greatly benefited from a standardisation of gauges, which enabled the same design to be used in many city and old trams being sold on.

Engineering Change

Another reason why systems can get locked into particular solutions is the effort involved in changing a system or the design of a system. The design of nearly all complex products or system is incremental as a way to reduce the design effort and the risk associated with novel solutions. Companies often aim to meet new requirements or achieve new aims by changing as little as possible and as much as necessary (Eckert et al. 2012). It is, however, rarely enough to define the new requirements at the beginning of a project, projects change throughout the development process as new requirements emerge, and these changes affect other parts of the system. As many subsystem or components cannot be changed, for example, because they are on order, too connected to other subsystem, or too costly to change, accommodating change request is a complex and costly operation.

Before defining engineering change, we need to distinguish it from change management, which is a term from the business literature referring to the administration and supervision of organisational transformation (Kettinger et al. 1997). The term *engineering change* refers to required redesign, whereas *engineering change* *order* is the directive to make the required change. In the literature, engineering change has been defined in a variety of subtly different ways – three definitions are:

- “An engineering change (EC) is a modification to a component of a product, after that product has entered production” (Wright 1997).
- “[Engineering changes are] the changes and modifications in forms, fits, materials, dimensions, functions, etc. of a product or a component” (Huang and Mak 1999).
- “Engineering change orders (ECOs) – changes to parts, drawings, or software that have already been released” (Terwiesch and Loch 1999).

The difference in these definitions lies in the timing of when a change occurs. Wright’s (1997) definition restricts engineering change to when a product is in production or in use, whereas Terwiesch and Loch (1999) see change as occurring once a design or part of the design has been released. Huang and Mak (1999) address the aspects of the design that can be changed and define the scope of the change, but do not comment on the timing when a change occurs. Jarratt et al. (2004) have synthesised these differences and offer the following definition which will be adopted for this chapter: “an engineering change is an alteration made to parts, drawings, software, or people that have already been released during the product design process. The change can be of any size or type; the change can involve any number of people and take any length of time”. This definition may be easily extended to cover complex socio-technical engineering systems with the addition of the consideration of people as part of the system description.

It is important to differentiate engineering change from iteration. Iteration occurs in many different ways as designs purposefully converge towards release (Wynn and Eckert 2017) and are an integral part of the evolution of design processes. Change is an active revisiting of a task that has been considered completed (Jarratt et al. 2011). Therefore, change is often seen as problem or as something that needs to be minimised.

The Engineering Change Process

Engineering change can be seen as a form of process, albeit on a much smaller scale. As with other design processes, it follows a high level a generic structure but of course varies in the details according to organisational, market, and product issues (Pikosz and Malmqvist 1998). Figure 3 shows a generic process proposed by Jarratt et al. (2004). Changes are either initiated, triggered by new requirements arising from the customers or clients or from other teams in the organisation, or emergent, in response to a problem identified during the development processes or in use (Eckert et al. 2004). The cost of changes goes up as the design processes progress and more decisions are confirmed that might need to be undone. In particular, the cost goes up when not only the design but also the prototype and production tooling need to be changed. For example, Terwiesch and Loch (1999) compared two similar changes in an automotive company, where the change costs less than $10,000 before any tooling is commissioned and approximately $190,000 afterward. Several authors

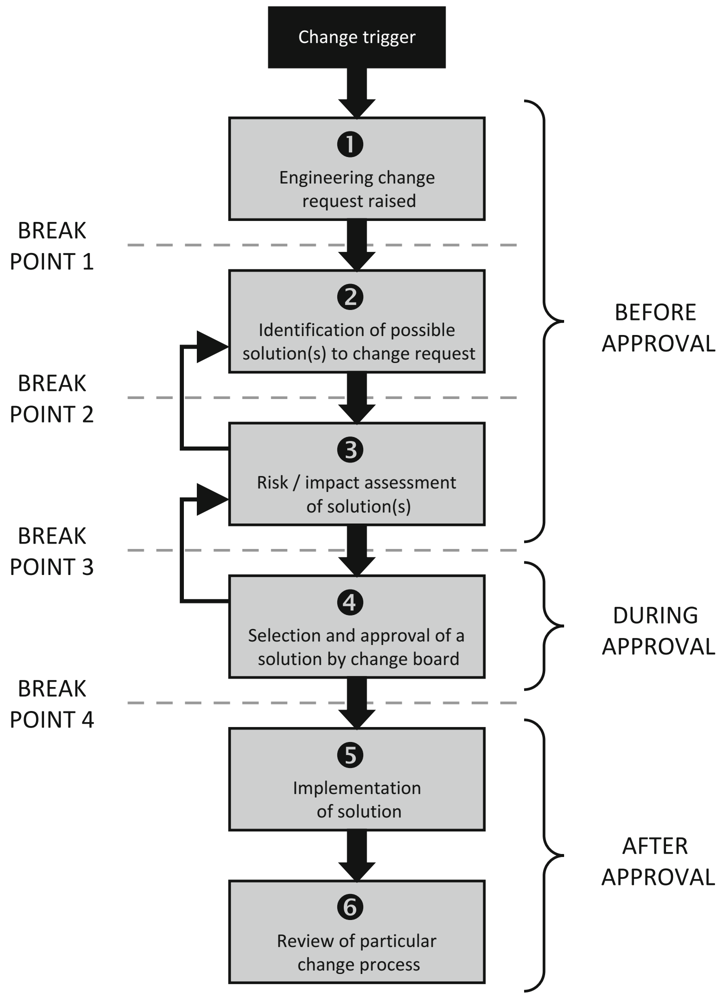

Fig. 3 A model of a generic change process from Jarratt et al. (2004)

also quote a "Rule of 10" for cost associated with a similar delay in the timing of a change (e.g., Clark and Fujimoto 1991; Anderson 1997; Fricke et al. 2000).

A change is usually raised through an engineering change request (ECR) or engineering change proposal (ECP), "a form available to any employee used to describe a proposed change or problem which may exist in a given product" (Monahan 1995). Once a request for a change is raised, potential solutions can be identified, each of which may be associated with a certain risk, cost, or opportunity. At this point, a suitable solution is typically selected and carried out. The change is then requested in an engineering change order (ECO) or engineering change notice (ECN) – "a document which describes an approved engineering change to a product and is the authority or directive to implement the change into the product and its documentation" (Monahan 1995). On completion, the changes are usually reviewed. Most companies have engineering change boards or approval committees, who meet periodically or in response to crises. Changes are often bunded and assessed together, as they may affect each other, so that a new version of the system can be released. The change board typically decides whether the proposed change adds value overall and, as a result, change requests are also often rejected. As Clark and Fujimoto (1991) point out, it is vital to differentiate between meaningful and meaningless changes. The same logic applies to change as applied to socio-technical engineering systems. Engineering companies are, however, more likely to follow a structured and formal process than a socio-technical engineering system, which is also subject to political decision-making and changes in human behaviour as the example of the tram system has shown. In the history of the tram development, there are many points, for example, when the local infrastructure was not updated in the UK, where a systematic consideration of alternatives and an assessment of the associated risk to the entire system would have been beneficial.

Engineering change plays an important role in configuration management, in particular as companies need to comply with configuration management and quality management standards such as ISO10007 (ISO 2003) and ISO9001 (ISO 2008), which demand clearly documented processes for all key business activities. According to the IEEE Standard Glossary of Soft Engineering Terminology (IEEE-Std-610.12-1990), configuration management is "a discipline applying technical and administrative direction and surveillance to identify and document the functional and physical characteristics of a configuration item, control changes to those characteristics, record and report change processing and implementation status, and verify compliance with specified requirements", where the item may be software or more generally a system. The systems engineering community focuses on configuration management on the integrity of a single system across its lifecycle. For example, they would look the tram system in a city to make sure that a new tram would still be able to stop at all stops and go around all corners on the existing rails. Whereas in engineering design the focus is often placed on different configurations offered by option packages are internally consistent (Jarratt 2004). For example, if the tram builder offered different versions of models with different internal configurations, they need to make sure that every change, such as a new air-conditioning system, still works on all those versions.

The Causes of Engineering Change

While the process by which a change is carried out is fundamentally the same, the causes of changes do vary and with them the attitude of engineers to the changes. Changes fall into two categories: those responding to emerging problems with the system and those that aim to improve or adapt the system in response to new requirements (see Fig. 4, Eckert et al. 2004, and Jarratt et al. 2011 for details).

Emergent changes arise from the properties of the system itself and are usually in response to problems emerging with the system throughout the system lifecycle,

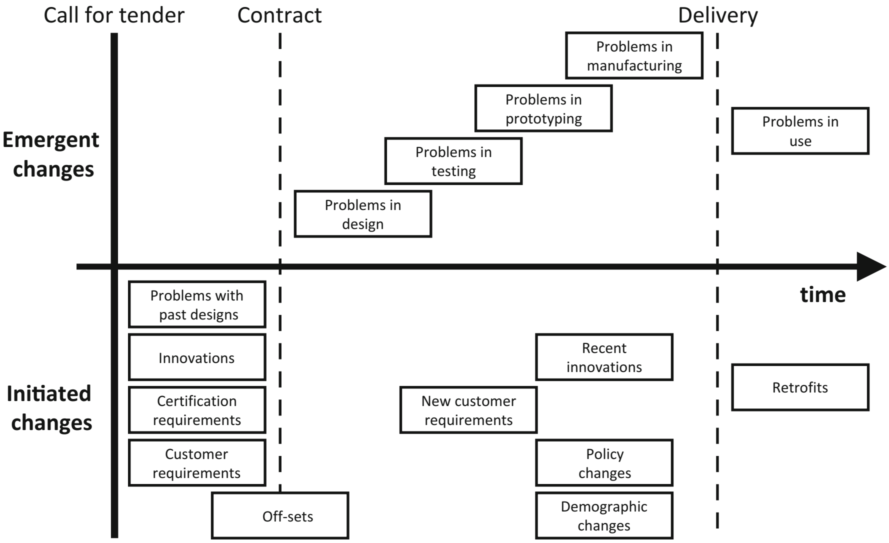

Fig. 4 Adapted from causes of change by Eckert et al. (2004)

from design and testing to prototyping and manufacturing as well as problems occurring in use. This includes:

- *Error or mistakes* that arise in the lifecycle where either wrong design decisions were taken or the design was executed in the wrong way. Many problems appear during system integration when the results from different teams, working in parallel, are brought together and it becomes clear that designers have worked with wrong assumptions or outdated parameter values.
- *Safety issues* that become apparent during prototyping or use. These can arise from a limited understanding of the use context of a system.
- *System quality issues* can occur from production not meeting the expected standards or a lack of understanding of the actual use or the factors affecting it, for example, humidity might lead to components rusting, or operator training may not meet the needs for safe system operation.

While errors are the result of a faulty implementation of requirements, safety and quality issues can arise from the requirements that have not been appropriately defined.

Initiated changes are intentional improvements, enhancements, or adaptations of a system can take on various forms. These can arise from the numerous stakeholders outside the system development team (see, e.g., Eckert et al. 2004 as an example of the causes of change for helicopter design):

- *Customers* change their minds during the system development process. They might ask for better performance or different functionality. This can be an issue for systems engineering design, as complex systems have long development times and therefore time for customers to change their mind. If the customer is a political body, like many customers for tram systems or defence systems, changes in government can also lead to changes in requirements. In practice, it may be more economic to postpone performance improvements to the next generation of systems (Fricke et al. 2000). For many systems, it is also faster to complete the system to existing specifications and then change it once it is delivered to customers, rather than wait for time-consuming formal change approval processes to take place.

- *Sales and marketing* can act on behalf of multiple customers and also respond to perceived market trends or market opportunities. It can be difficult for sales and marketing departments to understand the engineering implications of changes that they are demanding.
- *Production and maintenance* experts often see the potential for improvements in systems that might make them easier or cheaper to produce or maintain.
- *Suppliers* pass on suggestions for improvements or change their own systems and therefore force their customers to accommodate such changes. For example, the same diesel engines are supplied to numerous equipment manufacturers, who have to accommodate engines meeting new emission legislation. See Rouibah and Caskey (2003) for a review of supply chain issues in change management.
- *Systems engineering* also identifies ways to improve the system, for example, as new technologies are introduced. Changes by systems engineering would typically be bundled and introduced as a new system release.
- *Company management* takes strategic decisions that can affect a system, for example, when suppliers are changed and new system technologies are adopted.
- *Legislators* play a very significant role in system changes, as the need to meet new legislation or certification requirements obliges companies to respond (adapted from Jarratt et al. 2003).

During the system development process, the balance of changes to likely to shift from initiated changes at the beginning to emergent changes as a system is "designed" (Kanike and Ahmed 2007; Vianello and Ahmed 2008; Sudin and Ahmed 2009).

Connectivity Leading to Change across the System

Many changes are not caused by external factors or immediate problems but by other changes which may have knock-on effects across the system. For example, if a tram operator buys larger trams, they might need to make changes to platforms if they are not long enough. This is an example where the consequences of the changes are easy to predict and fairly direct. However, in other cases, the effects are more indirect and harder to predict, for example, if house prices rise as a result of the larger trams which are more comfortable to use and people change from cars to trams. This also applies to technical changes within a socio-technical engineering system. For example, if trams are fitted with better air-conditioning systems, it might be necessary to refurbish much for their interior, because existing air ducts might not be big enough and internal panels cannot accommodate them. If the changes are well thought through this, knock-on cost can be factored in, but often engineering companies have nasty surprises when the change costs spiral out of control as knock-on effects are discovered too late.

Other changes are frequently cited as causes for changes, for example, Rowell et al. (2009) found in a case study that 36% of change requests included "other design change" as the cause. Giffin et al. (2009) analysed 41,500 change requests generated during the design of a complex sensor system over 8 years to see the dependency between different changes. They found that only about half of the changes were approved; in particular, change requests for some areas were consistently rejected because they did not have the in-house expertise to carry out changes to some legacy systems. As Fig. 5 shows, changes that are rejected are often substituted by other change requests that also can deliver the desired result. This results in a network of connected parent, child, and sibling changes.

Whether a component or subsystem can absorb a change or pass it on to other components or systems depends on the current stage of the system. For example, many tram stops are longer than the current trams and can therefore accommodate a larger tram, but there remains an amount of increase that exceeds their capacity to cope which will result in the need for an extension.

Eckert et al. (2004) (Fig. 6) therefore classify elements of a system into:

1. *Absorbers*: these can be either *partial*, containing many changes and passing on only a few, or *total*, causing no further change while accommodating a number of changes (a rare situation).
2. *Carriers*: neither reduce nor add to the change problem, they merely transfer the change from one component to another.
3. *Multipliers*: expand the change problem making the situation more complex, which may result in an "avalanche" of changes.

Change can generate clusters of connected changes. Giffin et al. (2009) discovered several large clusters of changes, the largest of which involved 2566 connected change requests, the second 445, and the third 170 changes. Typically, a change issue must be resolved, with all its follow-on changes, within a particular time t. However,

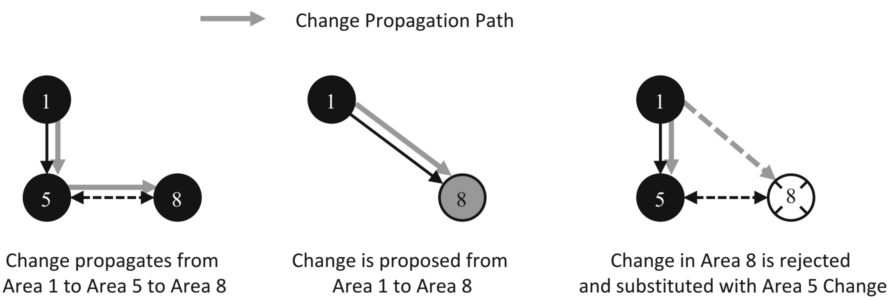

Fig. 5 Change propagation paths from Giffin et al. (2009)

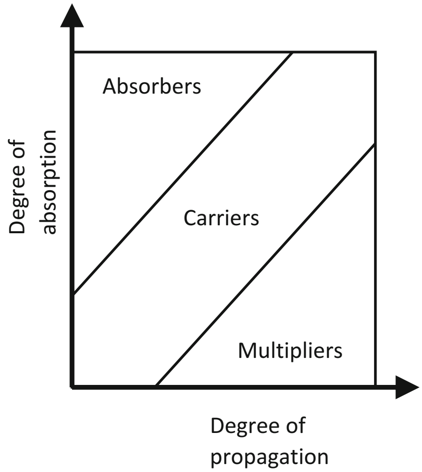

Fig. 6 Representation of the change propagation characteristics of components from Eckert et al. (2004)

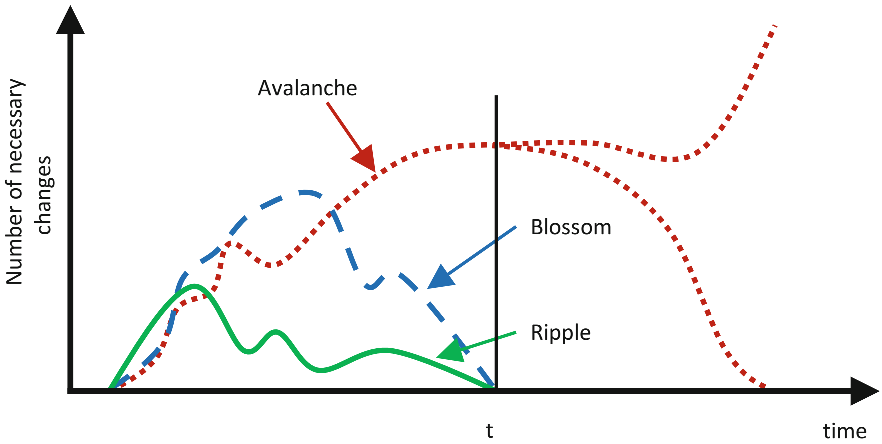

Fig. 7 Different patterns of change propagation from Eckert et al. (2004)

this may not always be the case, and, from the perspective of a particular point in time, the profile of changes can be classified (Eckert et al. 2004 and Fig. 7) into the following:

- *Ending change propagation* – consists of *ripples* of change, which are a small and quickly decreasing volume of changes, and *blossoms*, which are a high number of changes that are brought to a conclusion within an expected time frame (marked by a "t" in Fig. 7).
- *Unending change propagation* – characteristic of this type are *avalanches* of change, which occur when a major change initiates several other major changes, and all of these cannot be brought to a satisfactory conclusion by a given point in

time. Fricke et al. (2000) also talk of an avalanche of engineering change, while Terwiesch and Loch (1999) refer to “a snowball effect”. After this time, in some cases, additional resource can be used to bring the problem to a conclusion; however, occasionally the project has to be terminated.

Giffin et al. (2009) advocate that multipliers are good candidates for more focused change management. They also found ripples, however, in their data set where the peak of cyclical change activity occurred late in the program driven by rework discovered during system integration and functional testing.

In systems engineering projects, the implications of change can be difficult to predict, because not only do the changes need to be identified and implemented, but they also need to be validated across the entire system. To avoid change avalanches, it is important to adhere to the guidelines for handling engineering change proposed by Fricke et al. (2000), who advocate to (1) avoid change in far as possible; (2) handle change as soon as possible; (3) focus on the effective change and (4) handle them efficiently; and (5) learn to handle changes better over time through continuous learning.

Connecting Parameters and Margins

Whether a change propagates depends on the nature of the coupling that leads to the change. Several key couplings can lead to propagation (Terwiesch and Loch 1999) (1) between components and manufacturing, (2) between components within the same subsystem, and (3) between components in different subsystems. In addition, patterns of use also can lead to changes across the system. For example, a decision to make tram systems accessible to wheelchair users has not only led to some models of trams becoming obsolete and ramps being installed to the entrances to others but also to raising platforms and the addition of ramps to platforms.

Components and systems are linked to each other through a number of different parameters. For example, one of the parameters that links the trams and platform is the length, as is the height of the tram that is linked to the height of the platform. Jarratt et al. (2004) clustered such parameters into linkage classes, for example, as geometric links or thermal links that can be looked at in together (Fig. 8a). They found that engineers are often aware of the geometric connections but forget to consider the less obvious ones, like thermal links, that can cause vibrations if components expand under certain operating conditions and touch neighbouring components. This type of linkage analysis could then be easily adapted for socio-technical engineering systems (Fig. 8b) by modelling different types of connections. For example, different tram lines are connected by the people that change from one line to the other, by the rolling stock that operates on several lines and the pieces of track that are used by several lines. So, if a new suburb is built and the number of passengers on one line increases, rolling stock might be shifted to that line or the frequency of the trams is increased. This in turn would affect the working patterns of the drivers. Some connections, like the fact that the different lines have a shared ticketing system, might not be relevant to a change in passenger numbers.

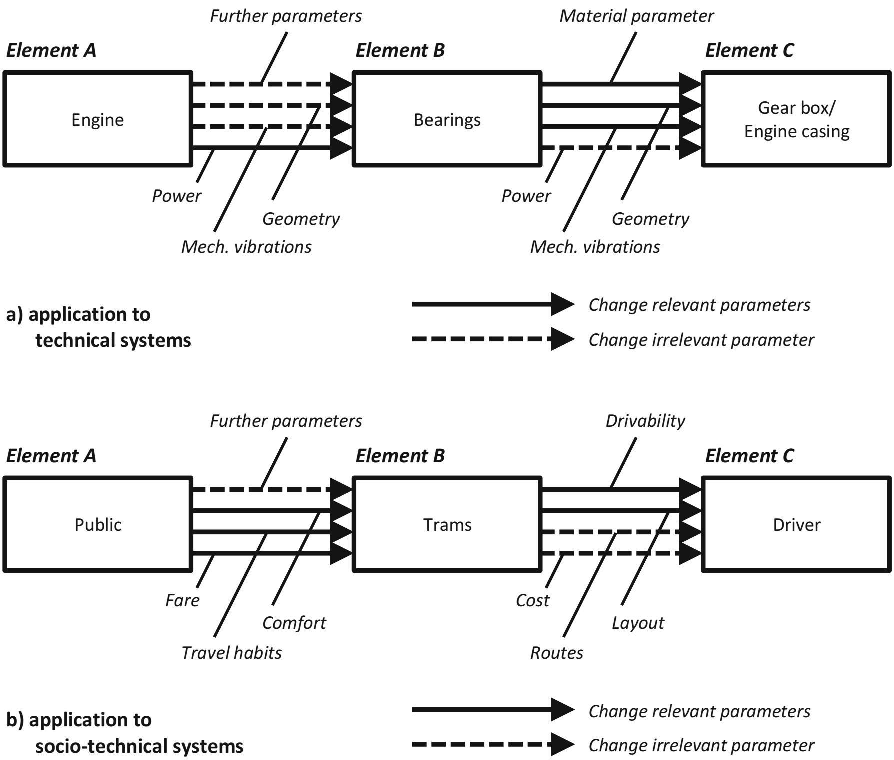

Fig. 8 Different parameters connecting the components of a product (**a**) or the elements of a system (**b**)

Changes only propagate if they are not absorbed by margins on the component. For example, a tram can carry a certain amount of sitting and standing passengers, which is stated in the tram. However, most of the time trams are not full and have excess capacity. Usually there is a certain amount of buffer and more people can be fitted in; however, there is a limit to the amount of people who can enter the tram. Eckert et al. (2019) defined margins formally in terms of the requirements for the system, **Req**, the constraints, **Const**, on the design, and its capability, **Cap**, as shown in Fig. 9.

Margins have two aspects: buffers **B** against uncertainties and genuine excess **E** that can be used in a new design. For example, we could think of a margin on the lengths of the tram stop. There is uncertainty on exactly where the tram comes to a stop, so there is a buffer on the length, but beyond that there is excess. If the excess is big enough, the operator could decide that a second tram line or a bus could share the stop, because both can fit one behind the other. The concept of excess has been analysed by Tackett et al. (2014) in the context of ship refurbishment, from the perspective of how a design can be upgraded. They identified excess as the “the

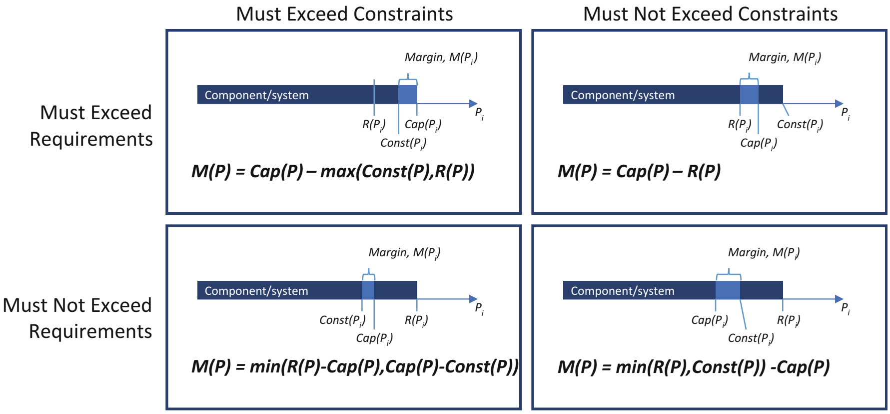

Fig. 9 Margin (light blue bar) between requirements and capabilities for a component or system from Eckert et al. (2019)

quantity of surplus in a system once the necessities of the system are met", while acknowledging that system design is subject to uncertainties.

A fully optimised system would have no excess margin in any of its parts. However, excess provides the ability to respond to new external requirements without redesign, as well as changes to requirements which arise from the system development process itself owing to knock-on effects of changes from one component or subsystem to another. The distinction between buffer and excess is particularly important since parts of the buffer can move to excess, particularly if the source of uncertainty that the buffer caters for is removed, i.e., by carrying out a test or by freezing a parameter.

Change Propagation

Given the impact of change propagation across a complex system, it is vital that companies understand the effects of a change before committing to it. As changes propagate through the connections between different parts, this connectivity needs to be understood. Many change predication approaches are based on design structure matrices which provide a simple means of representing parts and their connections.

Mapping Dependency

Design structure matrices (DSM) and domain mapping matrices (DMM) were first proposed by Donald Steward in the 1960s but really took off with a widely cited paper in the 1980s (Steward 1981), when the work was taken up by systems engineering researchers at MIT (Eppinger 1991). Tyson Browning provided highly cited review papers in 2001 (Browning 2001) and 2015 (Browning 2015) as well as a book with Steven Eppinger, where DSMs were applied to 44 industrial examples (Eppinger and Browning 2012). This chapter will only summarise the key ideas.

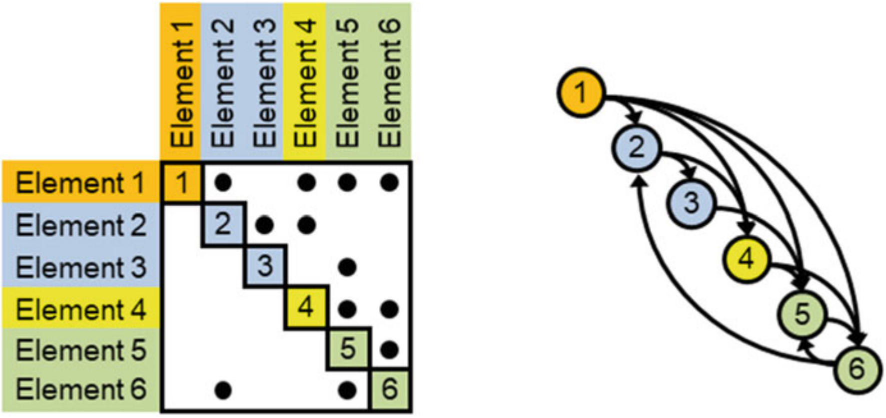

Fig. 10 Example of a binary DSM with optional rows and column labels and its equivalent node-ling diagram from Browning (2015)

Browning (2015) provides the following introduction: "A DSM [..] is a square matrix where the diagonal cells typically represent system elements (such as components in a system, people in an organisation, or activities in a process) and the off-diagonal cells represent relationships (such as dependencies, interfaces, interactions, etc.) amongst the elements. Binary DSMs, as shown in Fig. 10, indicate that a link exists, other DSMs have number to quality the connection and indicate for example a probability of change propagating or a strength of connection, while others have use numbers or symbols to indicate the nature of the link".

Dependency matrices have been used by many researchers, so that both "input in rows" and "input in columns" versions exist; however, many researchers have adhered to the Steward conventions of "input in rows". While the DSM is the equivalent of a directed graph, many prefer a matrix representation to the graph as the architectural elements are more visible in a matrix. However, a matrix makes it more difficult to identify propagation paths (Keller et al. 2006).

The applications of DSMs fall into three categories: models of systems, models of processes, and models of organisations. System DSMs are widely used to model dependencies between components or between functions to analyse the system architecture, i.e., the arrangement of the functional elements into physical blocks (Ulrich and Eppinger 1995). DSMs that map the modular structure and interfaces have been applied in numerous industry sectors. Organisation DSMs map the connectivity between teams or people and have been used to structure organisations and improve aspects of the running of organisation, such as communication. Process DSMs typically map the input-output relationships of process tasks to plan and improve processes (e.g., Clarkson and Hamilton (2000), Lévárdy and Browning (2009)) by avoiding unnecessary iteration (see Browning 2009; Yassine et al. 2003) and optimising the overlap of tasks (e.g., Meier et al. 2015). DSMs have also been used to analyse the alignment between system, process, and organisational structure (e.g., Sosa et al. 2004).

Browning (2001) distinguished between static DSMs where all the elements in DSM, such as components or teams, exist contemporaneously and time-based DSMs, where the input to one element is the output of another. Static DSMs can be analysed with cluster algorithms, which restructure the matrix in a way that maximises the connectivity within a cluster and minimises the connectivity between clusters. This approach is used, for example, for identifying suitable team compositions (e.g., Sanchez and Mahoney 1996) or architectural modules (e.g., Pimmler and Eppinger 1994). Time-based DSMs can be analysed through sequencing algorithms, which have the aim of minimising the dependency on information generated by tasks that occur later on, thus forcing iteration in a process. Partitioning is a form of reordering of the matrix so that it has an "upper triangular" form, i.e., tasks do not depend on inputs from later tasks, which would be marked below the diagonal (see Browning 2001 for an overview). Once coupled blocks of activities are identified, several operations are available:

- Aggregation, which might provide simpler models but not necessarily simpler processes
- Decomposition, where lower-level activities are investigated to identify alternatives that do not create coupling
- Tearing, where the least critical connections are removed and the matrix is restructured to find the smoothest possible process (see Steward 1981; Eppinger 1991; Eppinger et al. 1994)

Clusters of tasks can also be broken up by specifying the level of information quality required to start new tasks (Clarkson and Hamilton 2000; Lévárdy and Browning 2009; Wynn 2007). Once restructured, the DSM can be used to develop process schedules, which have optimised the grouping of tasks, the overlap, and the parallelisation of tasks (Smith and Eppinger 1998; Cho and Eppinger 2005; Eppinger and Browning 2012).

DSMs typically have the same type of elements, i.e., all process tasks or all system elements. DMMs (domain mapping matrices) map different types of elements against each other (Danilovic and Browning 2007), such as functions and components as in the design matrix used in axiomatic design (Suh 1990). Multiplying a DMM with its transpose yields either a component-component or a function-function matrix. MDMs (multiple domain matrices) integrate DSMs and DMMs into large mappings, e.g., a MDM of function and components includes the component-component matrix, the function-function matrix, the component-function DMM, and the function-component DMM (Lindemann et al. 2008).

Model Granularity

Models are abstract representations of their target system, the part of reality they choose to capture, and are created for a specific purpose (Frigg 2003). Many different models can be generated of a system, and how these models are constructed is influenced by how exactly the models are created and what assumptions go into building the models.

The results of the analysis of models, such as DSMs, are largely influenced by the granularity of the model that is analysed, as shown by Chiriac et al. (2011) for modularisation and Maier et al. (2019) for process planning and change prediction. Model granularity refers to the level of detail, i.e., grain size, in a model or resolution of the model. Maier et al. (2017) provide a detailed overview of different concepts relating to granularity and propose a framework of model granularity which distinguishes between structural granularity, i.e., the level of decomposition, and the relationships between the elements and information granularity, which involves both the information in a granule and the resolution of the analysis (Fig. 11). This concept, and associated consequences, can be illustrated by its application to DSMs (Fig. 12).

Change Prediction

Given the risk of change propagation, companies want to predict the propagation of engineering change. Change propagation is not a deterministic process, because change requests can be rejected, as reported in Giffin et al. (2007), and other teams might handle the changes they are confronted with in different ways than anticipated (Eckert et al. 2005). As argued in section "Connecting Parameters and Margins", a certain amount of change can often be absorbed, because a change affects a component and therefore could lead to change propagation. This means that changes are probabilistic, and experts have to make a judgment whether a particular change will affect another component and by how much.

The change prediction method (CPM) was developed to show how changes might spread through a system (Clarkson et al. 2001, 2004) and uses a design structure

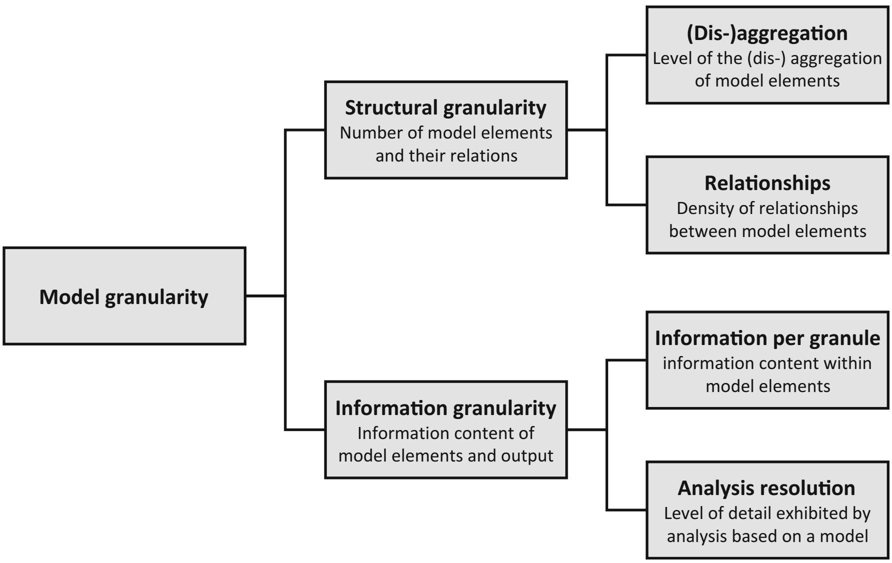

Fig. 11 Different dimensions of granularity from Maier et al. (2017)

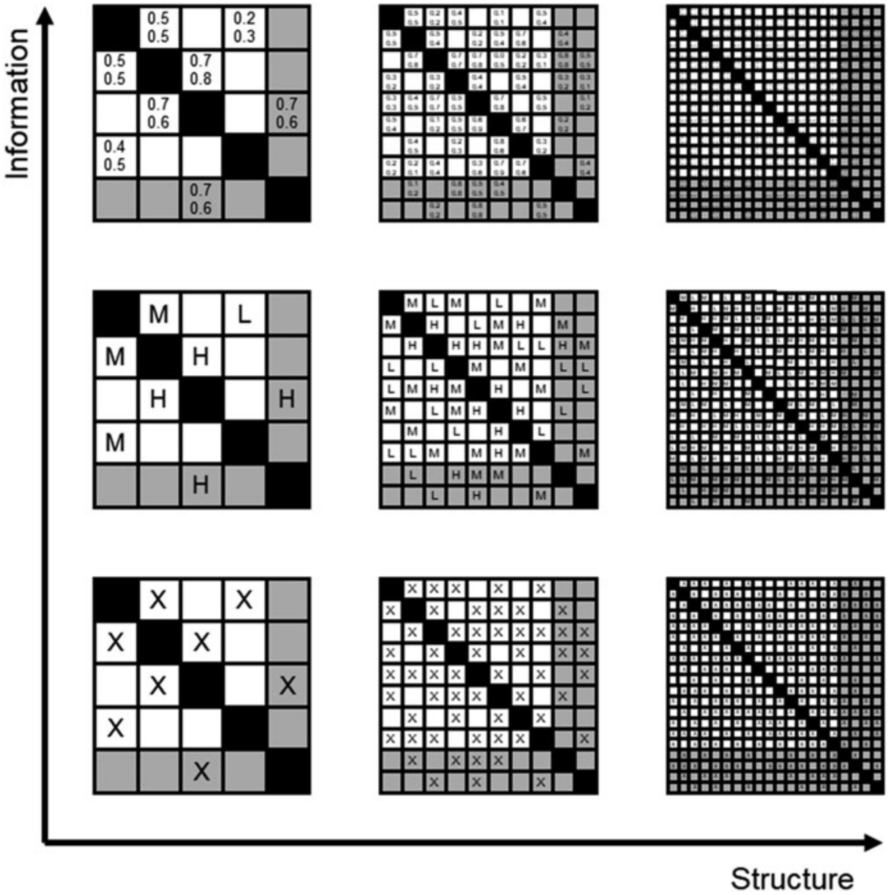

Fig. 12 Structural and information granularity of a DSM from Maier et al. (2017)

matrix (DSM) as the basis of the system model. For each connection, the risk of a change spreading is captured as a product of likelihood times impact, where both are expressed on a high medium and low scale. The system model starts with a direct likelihood and direct impact matrix and multiplies the values of these to obtain a direct risk matrix, as the algorithm assumes that a change to a component would not come back on itself and uses a route counting algorithm to calculate the combined risk of change propagation (Keller et al. 2009). Based on empirical evidence, the algorithm calculates up to five levels of change propagation. Alternatively, DSMs can be multiplied using classical matrix multiplication; however, this includes change coming back to the component (Browning 2001, 2015). Whether and how a change propagates not only depends on the level of connectivity within the system but also on the process with which the change is carried out.

Ahmad et al. (2013) extended the CPM approach to include process considerations, while Koh et al. (2012) combined CPM with a house of quality approach to incorporate changes to requirements in change prediction. Morkos et al. (2012) tackle change propagation through requirements directly by generating a requirement DSM which is multiplied with itself to generated high-order DSMs which show the effect of requirement changes on other requirements. As a change to a component can also affect the functions a component carries out, these functions can also propagate changes. Hamraz et al. (2015) combined CPM with the function-structure-behaviour model by Gero and Kannengiesser (2004) into a very large multiple domain matrix (MDM). Grantham Lough et al. (2006) developed change prediction and risk assessment methods for functional decomposition, based on function failures (Stone and Wood 2000) of the system in early design stages using data from past changes through the use of a failure mode and effects analysis (FMEA) approach.

An even broader range of connections is considered by Pasqual and de Weck (2012) who use DMMs to model change on three layers, a product layer (similar to CPM), a change layer which looks at the connection between the change requests building on the work by Giffin et al. (2009), and a social layer, which addresses the communication of the engineers. They also address the connections between these different layers as changes can be requested on each level and therefore provide a link that might or might not lead to an actual change. They calculate a change propagation index which expresses the number of changes coming in and out of a product as wells as a change acceptance and a change reflection index, which gives them a proposal acceptance index.

Rutka et al. (2006) reported a change propagation analysis (CPA) method utilising a dependency model supporting multiple linkages between pairs of information items, where linkages varied by type and level of change at both initiator and target of change. The model is searched for matching triggers and propagation paths followed, enabling final impacts and likelihoods to be computed. The CPA approach requires even more information to populate its model and its assumptions on final change levels (use the worst case), and frozen items simply stopping a propagation path may not always hold true. The authors indicate that the method has been tested in aerospace case studies, but results have yet to be reported.

Reddi and Moon's (2009) approach is another dependency model technique, harvesting dependencies in the early phases of design for use in later stages of the lifecycle. It captures the type of change at both initiator and target and the likeliness of the specific change propagating between the two in terms of discrete levels (low, medium, or high). Search algorithms iterate through the model to identify all possible propagation paths. The method requires a dynamically evolving ontology and model as it is unlikely that all dependencies and dependency types will be captured during early design.

Most recently, Kocar and Akgunduz (2010) have developed a hybrid engineering change management and virtual reality collaborative design system to create the ADVICE (active distributed virtual change environment) prototype. Engineers can raise, view, and accept/reject proposed changes in a graphical visualisation of the system, akin to a computer-aided design (CAD) or virtual reality view. This is coupled with a database of engineering changes, which is searched by data mining agents, both to identify prior attempts to raise the same or similar changes and to predict possible change propagation, by detecting patterns of repeated events in the change records. The tool has yet to be tested on a real-world case study, and the authors suggest that they may need to adapt their algorithms to better reflect the non-ideal nature of actual change case records.

While these former examples focus primarily on technical systems, CPM and MDMs can also be used to explore socio-technical (Hassannezhad and Clarkson 2018; Hassannezhad et al. 2019) or even social systems. Figure 13 shows an MDM exploring the feasibility of mapping responsible areas of government to the consequences of actions related to the tackling of COVID-19. In this example, a mapping of consequences to responsibilities is aggregated from multiple resources and then used as the basis for applying change propagation and clustering algorithms to identify connectivity between consequences or responsibilities. This in turn raises

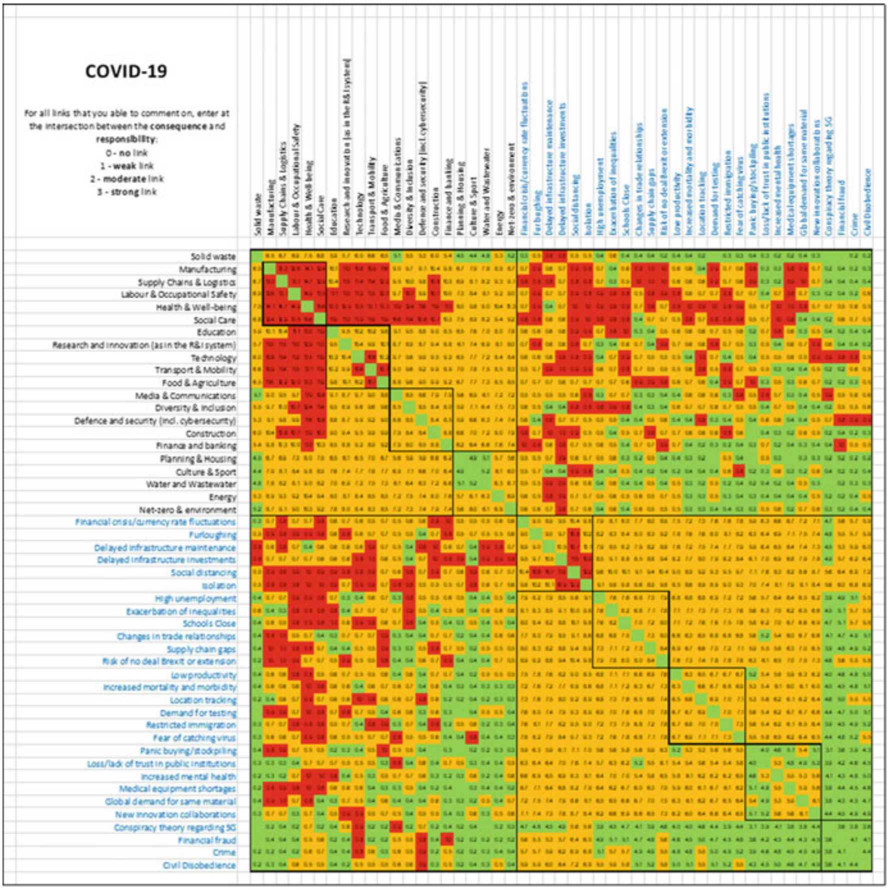

Fig. 13 Connectivity between areas of government linked by common consequences

questions that might lead to improved coordination between otherwise disparate areas of government or policy programs targeting related consequences.

The Design of Resilient Systems

Complex socio-technical engineering systems are usually huge investments that are maintained over long periods of time. They evolve as existing elements and are upgraded and others are inserted into the system; however, throughout they need to keep their core functionality going. For example, while tram tracks are upgraded, the operators need to offer a replacement bus service, for which they need to have the buses available. The systems need to be resilient to change. However, this resilience is not an emergent property or just the result of path dependency; it needs to be actively designed into the system. Somebody needs to take active decisions which aspects of the system are resilient and against which emergencies. For example, a transport system can offer multiple route to key places in a city. It is designed to cope in a particular with a certain amount of flooding or snow, but there might be a time when it closes down, and people are told to stay at home. To make a system resilient, choices need to made, based on a prediction of the future, which analyses the expected variability and considers paths of potential evolution.

Changes are an inevitable part of handling anything complex. Systems evolve over time and the requirements placed on them change. Even if the requirements themselves do not change, systems are affected by adverse events or simply by the passage of time. The tram systems wear out over time and need to be repaired and upgraded. The tram tracks wear thin, the trams have accidents, and the parts wear out. But the wider system also changes, as the habits of the travellers change and traffic on road has a different composition. To minimise, or at least manage, the disturbance, engineers try to design their system to handle change in a predictable way. This is discussed under a number of different terms. The systems themselves are also designed with known future changes in mind.

The ability of a system to withstand changes and adapt to them is frequently discussed as resilience of a system to handle changes that cannot or are not foreseen at the outset. Wied et al. (2020) distinguish systems subject to adverse events, adverse change, turbulence, favourable events, favourable change, and variation as well as between systems that are capable of recovery, absorption, improvement, graceful degradation, minimal deterioration, and survival.

Systems Responding to Adverse Effects

Different communities have looked at the issue of systems being affected by change from a number of different perspectives, with a particular focus on safety and operability.

Systems are designed to be safe and not to put their users or others at risk (Hansson 2018), where risk itself is a rich concept which covers multiple related meanings. Qualitatively, risk refers both to an unwanted event and to the cause of an unwanted event, for example, engine failure in an individual tram and power cuts on the national grid that stop multiple trams from running. Quantitatively, risk is the term used for different degrees of specificity from risk as a probability (the risk of tram drivers getting sick) to a statistical expectation value (the risk of traffic jams in the morning) to a known and accepted probability (a decision is taken to accept a risk of x% that not all trams are operational when ordering a certain number of trams). Hence, responses to safety-related risk can be classified in four distinct categories:

- Inherently safe design, which removes the source of the safety risk, for example, giving trams dedicated tracks and thus avoiding road accidents.
- Fail safe design, which minimises the impact of any failure, for example, by having bus routes that can be diverted to cover the route of a blocked tram.
- Safety reserves, which involve an element of over-dimensioning, for example, by having additional trams or buses on standby.
- Procedural safeguards, which focus on human processes, for example, training tram drivers so that they are able to counteract any safety risk.

A key emphasis in the safety engineering community is placed on the validation of the system against typical and worst-case scenarios. Systems are subjected to rigorous physical and virtual testing to assure system safety. Safety engineering is also concerned with defining appropriate safety margins (additions to parameters by a certain amount) or safety factors (multiplications of the parameter value by a certain percentage), for example, many systems in the aerospace industry are designed to operate at 1.5 times the expected maximum load. Another approach is the inclusion of redundant systems that can come into play when the primary system has failed. Redundancy is achieved either by duplicating the entire system, by adding an additional identical module, or by substituting a different system with the same functionality (see Chen and Crilly 2014, for a discussion of different types of redundancy).

Safety issues are, however, not the only reason why a system might fail. Reliability engineering (e.g., Elsayed 2012), which is typically seen as a subfield of systems engineering, takes a broader view and concerns itself with all the steps in the system development process that have an impact on the system working across the its lifecycle. It thereby has similar ambition and remits to engineering design research but places a greater emphasis on failure analysis processes and methods as the drivers of system development, many of which are defined in industry standards. Reliability can be defined as the “ability to perform as required, without failure, for a given time interval, under given conditions” (IEC 60050-192 2015). While design for reliability (Crowe and Feinberg 2017) exists as a design approach in its own right, it is often seen from a number of perspectives:

- Durability is concerned with the ability of a system to function over long periods of time and places the emphasis on prolonged life under normal operation conditions (Cooper 1994), for example, companies aim to increase the system life or service interval of trams.

- Robustness is concerned with the insensitivity of a system against sources of variation, such as assembly tolerances or use conditions, and robust design aims to minimise the variation of system performance in spite of the many factors that influence it (Jugulum and Frey 2007; Taguchi et al. 2005); for example, trams would be expected to run in all weather conditions.
- Resilience describes the ability of a system to absorb external changes (Holling 1973), either by reverting back to an original state or by finding a new equilibration, where Woods (2015) differentiates this further into (1) resilience as rebound from trauma and return to equilibrium; (2) resilience as a synonym for robustness; (3) resilience as the opposite of brittleness, i.e., as graceful extensibility when surprises challenge boundaries; and (4) resilience as network architectures that can sustain the ability to adapt to future surprises as conditions evolve. See Wied et al. (2020) for a review of resilience concepts.

A resilient system maintains its core functionality no matter the circumstances it is exposed to. Resilience is also a socio-technical concept which considers the wider conditions of use. Rather than having prespecified worst-case scenarios and predefined states that can be fully tested, what constitutes resilience is different for different stakeholders (Taysom and Crilly 2017). Many systems are required to combine all four aspects of resilience and adapt to change as well as withstand acute events. Resilience is seen as a general property of a system and does not draw a distinction between the events that it needs to withstand on the short and long term. A specific form of resilient system would be a self-healing system that can identify and fix its own faults, a concept that has been applied to software systems and materials (Ghosh et al. 2007; Wool 2008).

In summary, resilience has moved on from its original *Oxford English Dictionary* definition of "the quality or fact of being able to recover quickly or easily from, or resist being affected by, a misfortune, shock, illness, etc.; robustness; and adaptability" to encompass a broader view of the mechanisms that might deliver resilience. This then focuses the debate on the appropriate choice of such mechanisms and the design of system architectures that may deliver resilience in different ways in different parts of the system based on technical and economic options available at the time.

Design for Flexibility

While engineering change aims at assuring that the system remains its integrity when requirements change during the design process and design for reliability aims to assure that the system will function to those requirements even through adverse or changing circumstances, the requirements themselves can change during the lifecycle of the system or the design. These approaches are usually covered under design for flexibility or design for changeability.

Rajan et al. (2003) define product flexibility as “the degree of responsiveness (or adaptability) for any future change in a product design and advocate a modified failure mode and effects analysis (FMEA), which considers potential future changes in a similar way to potential future failure”. According to Fricke and Schulz (2005), design for changeability has four aspects:

- Robustness, i.e., insensitivity to adverse events
- Flexibility, i.e., the ability to change easily
- Agility, i.e., the ability to change rapidly
- Adaptability to changing environments

These can be achieved following a number of principles: simplicity, which allows designers to understand and modify the system, for example, by having clear and transparent interfaces; independence which minimises the coupling within a system; and modularisation, which defines a system architecture of clearly defined and replaceable modules (Fricke and Schulz 2005). These principles are aspirations which are difficult to achieve for most complex systems and are, as Simon (1969) points out, “near decomposability”, i.e., involve a certain degree of coupling which is difficult or impossible to eliminate. However, systems can be designed in a way that minimises coupling, for example, by following Suh’s (1990) principles of axiomatic design. However, in practice many complex systems are highly coupled, as coupling and function sharing can enable designers to optimise key system properties such as weight or cost.

Often the concern is not about a specific system being flexible but the design of the system being flexible to accommodate slightly different requirements around the same core functionality. Design for flexibility is a key driver for the design of the system architecture and in particular platform design, which is discussed elsewhere in this handbook. Many of the standard approaches to the design of the system architecture have come from design flexibility (see, e.g., Martin and Ishii (2002), Suh et al. (2007), or Cardin (2014)).

Anticipating Future Changes

In some cases, potential changes can be anticipated, and the design can be carried out in a way that makes these changes easier to implement. De Neufville et al. (2006) advocate design options, with the example of paying for stronger foundations on a parking garage to have the options of adding a floor later. This is akin to financial options, where a small number of specific change scenarios are costed and the cost for enabling them in a present design is calculated. Then change thresholds are set and options are put in place according to the likely cost of putting the options in place and likelihood of requiring these changes (e.g., Mak et al. 2017; Maier et al. 2017).

Options are an example of parameter trade-off to facilitate change. Ross and Hastings (2005) map out a “tradespace”, which is the space of possible designs within a given set of design variables. The tradespace can also be thought of as margins on parameters, in which a change is possible. Set-based design (Sobek et al. 1999; McKenney et al. 2011) is based on a similar idea and represents design options by ranges of parameters that narrow during a system development process. Dawson et al. (2012) are using a simulation game approach to identify suitable margins on parameter to avoid reworking loops in design processes. Optimising margins to minimise the risk of future changes is subject to ongoing research.

While it might be difficult to anticipate exactly what changes will occur at a later date, it is often clear that a system will have to evolve in the course of its life. Complex engineering systems such as transport or healthcare systems have always evolved and will continue to evolve as society and technology change. Designing evolvability aims to assure the changes involved in these evolutions can be carried out without undue negative effects. This is partially a matter to system architecture, with a clear modular structure and well-defined interfaces to minimise change propagation. Patou and Maier (2017) argue that adopting a systemic view and understanding the lifecycle of individual elements enables the stakeholders to adopt and design for evolvability principles and reduce the cost and pain associated with evolving system.

Conclusions

Complex socio-technical engineering systems are rarely designed from scratch to remain unchanged over their entire lifecycle, but rather most evolve over many years. They are altered and upgraded, and parts might be removed or people might transition, other parts added, and behaviours and policies change. These were the words at the beginning of this chapter. The ensuing narrative of the evolution of tram systems provided insights that added to our understanding of social-technical systems in general and to their evolution in particular. It demonstrates the impact policy approaches and constraints can have on large systems and shows how a complex system is affected by past decisions through path dependency. It highlights how an understanding of change propagation and prediction can influence the delivery of resilient systems.

Systems change over time, not only in terms of their functionality and behaviour but also as a direct result of changes in user habits and expectations. Such changes can be the result of aging technology, competing alternatives, policy change, changing customer needs, changing value propositions, resource constraints, and integration with other systems (amongst many other things). Whatever the cause, changes can have an impact across all parts of a system, particularly when dealing with complex socio-technical engineering systems where changes can propagate across engineered and human components. Such propagation can lead to unexpected, and seemingly unpredictable, results that may compromise the overall performance of the system. Before decisions about complex socio-technical systems can be made, it is necessary to think through the intended but also the untended changes and not only in the immediate future but also the long term. The example of the trams illustrates that early decisions taken about routes can have effects on entire cities for decades and centuries to come.

The evolution of socio-technical engineering systems may lead to changes in the system architecture and boundary and mix of technical and human elements, each of which will have an impact on the ongoing resilience of the system to further change. Conversely, the design of a resilient architecture from the outset may significantly reduce the cost of change over time and extend the useful life of a system. Designing in resilience and the ongoing management of change both benefit from knowledge of the inherent change properties of the system and designers' ability to predict or forecast the impact of future change as part of the system architecting process. However, despite best efforts, the long life of many socio-technical engineering systems makes adequate forecasting difficult, and time-dependent constraints can play a significant role in the long-term success or failure of such systems.

In summary, complex socio-technical engineering systems evolve over time, challenging original expectations of utility, efficiency, and measures of success. Resilient systems, which are designed to overcome some of these challenges, are themselves only the product of designers' abilities to forecast future use and predict the impact that this might have on the system architecture and detail design. Therefore, design methods that assist with such forecasting and change prediction have an important role to play in the design of complex socio-technical engineering systems.

Tram systems have undergone significant change over many decades, with their resilience tested by local political, cultural, and economic change. Of those that have survived, some provide a viable and valuable alternative form of local transport, while others have seen significant decline in revenue and investment. However, there may be a resurgence in popularity as local transportation needs change in the wake of COVID-19.

Cross-References

- ▶ Designing for Emergent Safety in Engineering Systems
- ▶ Designing for Technical Behaviour
- ▶ Dynamics and Emergence: Case Examples from Literature
- ▶ Engineering Systems in Flux: Designing and Evaluating Interventions in Dynamic Systems
- ▶ Engineering Systems Interventions in Practice: Cases from Healthcare and Transport
- ▶ Flexibility and Real Options in Engineering Systems Design
- ▶ Public Policy and Engineering Systems Synergy
- ▶ Transforming Engineering Systems: Learnings from Organising Megaprojects

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Sustainable Futures from an Engineering Systems Perspective

5

Tim C. McAloone and Michael Z. Hauschild

Contents

T. C. McAloone (✉)
Department of Civil and Mechanical Engineering, DTU-Technical University of Denmark, Kongens Lyngby, Denmark
e-mail: tmca@dtu.dk

M. Z. Hauschild
Department of Technology, Management and Economics, DTU-Technical University of Denmark, Kongens Lyngby, Denmark
e-mail: mzha@dtu.dk

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Abstract

Never before has the recognition of the need for solutions to the challenges of sustainability been greater. With a rising population of increasing wealth, we have recognised that humankind is "out of planetary compliance". Or in other words, we are borrowing from next generations, each and every day, with the direct negative effects of raising atmospheric temperatures (global warming), poisoning of our land and waterways, and threatening the biodiversity of the planet – to name but a few.

The response to these challenges is finally reaching critical mass. From Climate Summits, through United Nations Sustainable Development Goals, to Circular Economy campaigns, global action is happening. International associations, geographical regions, and individual countries are making bold moves to enact action against climate change. Measurements are being made on numerous sustainability goals. And the younger generation is successfully increasing its pressure on the incumbent world and industry leaders.

But how can engineering systems interpret these agendas and make a contribution to sustainability transition? What is the potential of taking a socio-technical holistic view on large and complex engineering systems, with a view to improving its sustainability performance? This chapter provides a brief overview of key sustainability developments in the past, which have laid the foundation for how engineering systems can contribute to a sustainable future through holistic socio-technical design. It also provides some paths forward for engineering systems, but some of the paving stones are still missing, so this chapter is also intended as a call to action.

Keywords

Circular economy · Engineering systems design · Life cycle engineering · Planetary boundaries · Sustainable development goals · Systemic sustainability

What Is Sustainability?

The year 1972 saw the publication of what would become a seminal report on the pressures of humans on the world's carrying capacity. The report, "Limits to growth", was submitted to the action group, the "Club of Rome", and the authors utilised the term "sustainable", to describe a global system that is "(1) sustainable without sudden and uncontrolled collapse and (2) capable of satisfying the basic material requirements of all of its people" (Meadows et al. 1972). Some years later, in 1987, United Nations' Commission on Environment and Development defined "sustainable development" as a "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development 1987). The focus in both definitions is on the fulfilment of human needs now and in the future, but the definitions do not specify which needs they are talking about. Whether it is the basic physiological needs, such as sufficient nutrition or shelter against a harsh climate, or needs belonging to higher existential levels, such as social recognition and self-actualisation (Maslow 1954), a fair definition of needs has become a central issue in defining sustainable futures. British entrepreneur and thought-leader, John Elkington, interpreted sustainability into a business context by identifying three dimensions of sustainability – the social, the environmental, and the economic – and introduced the concept of expanding from one (financial) bottom line to a so-called triple bottom line (subsequently popularly dubbed "people, planet, and profit") that a company that aims for sustainability needs to balance (Elkington 1997); see Fig. 2a.

In 2015, the three sustainability dimensions were further elaborated by the United Nations (UN) into 17 goals for a "universal call to action to end poverty, protect the planet and ensure that all people enjoy peace and prosperity by 2030". UN describes these Sustainable Development Goals as "a call for action by all countries – poor, rich and middle-income – to promote prosperity while protecting the planet" (Fig. 1). They recognise that "ending poverty must go hand-in-hand with strategies that build economic growth and address a range of social needs including education, health, social protection, and job opportunities, while tackling climate change and environmental protection" (UN 2020).

The first five goals specify the social dimension (People) of sustainability; the next seven goals the economic dimension (Prosperity); the next three the environmental dimension (Planet); and the last two goals introduce two new "P"s: Peace, justice, and strong institutions and Partnerships. The 17 Sustainable Development Goals (SDGs), with a total of 169 underlying targets, were adopted by all member states of the United Nations in 2015 and progress of the member states towards the targets is reported and monitored on an annual basis (e.g., Bertelsmann Stiftung 2020).

Fig. 1 Seventeen goals to end poverty, protect the planet, and ensure that all people enjoy peace and prosperity by 2030 (UN 2020)

Emerging Concepts of Sustainability

In the early 1970s, the researchers behind “Limits to growth” created future scenarios of the developments in global human population, food production, industrialisation, pollution, and consumption of non-renewable natural resources. These scenarios were used to investigate whether changes in the growth patterns for these five fundamental parameters might allow emergence of a sustainable feedback pattern for the interaction between human civilisation and the bio-geosphere. A significant finding was that one out of their three analysed scenarios led to a “stabilized world”, while the other two led to “overshoot and collapse” (Meadows et al. 1972). The idea that Earth’s finite natural resources and the limited capacity of the environment to absorb pollution posed absolute boundaries to the development and expansion of human societies were contested at the time. Over recent decades, however, the existence of absolute boundaries for our pollution of the atmosphere with greenhouse gases like CO_2 and CH_4 has gained not just scientific but also broad political acceptance. This was demonstrated in 2015 by the adoption of the so-called Paris Agreement targets, to keep our climate change impacts at a level where global atmospheric temperature increase remains close to 1.5 degrees above preindustrial levels (UNFCCC 2020).

The acceptance of absolute boundaries for environmental sustainability represents a shift in perspective from the traditional triple bottom line thinking, where the three sustainability dimensions (People, Planet, and Profit) can be traded off and a poorer performance in the environmental dimension can be compensated by an improved performance in the social and economic dimensions (Fig. 2a), to a new perspective (Fig. 2b), where the social and economic dimensions are nested inside the environmental dimension reflecting their dependency on the latter and the fact that while society would collapse without the services that it draws from the environment (mineral and biological resources, regeneration of clean air and water, soil fertility, etc.), environment would thrive well without society. The absolute limits posed by the environmental dimension (the planet’s life support

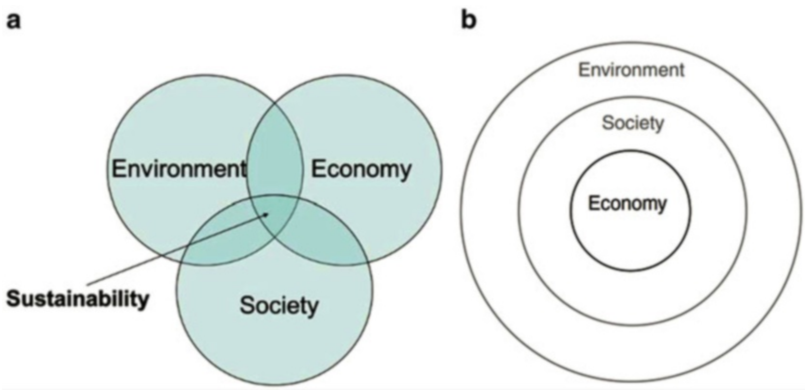

Fig. 2 Three dimensions of sustainability – from trade-off (**a**) to nesting (**b**). (From Giddings et al. 2002)

functions) have to be respected, and only when this is fulfilled are trade-offs between the three dimensions acceptable.

The implications of subscribing to the notion of absolute sustainability entail important changes in the way in which we understand the relationship between the triple bottom line considerations. Developing from an understanding trade-offs (between two or all three triple bottom line dimensions), towards an understanding of nested sustainability dimensions (within ultimate environmental boundaries, social and economic sustainability must be achieved), requires a necessary shift in thinking about interdependencies to achieve sustainability. All five of the parameters modelled in "Limits to Growth" (global human population, food production, industrialisation, pollution, and consumption of non-renewable natural resources) (Meadows et al. 1972) are in themselves socio-technical and systemic in nature. The choice of trading one dimension off against another is thus exchanged with a more complex and system-oriented problem. And the possibility of applying technical solutions alone to sustainability challenges develops into the need to think in terms of designing dynamic socio-technical systems, able of handling technical, social, and economic considerations and their interdependencies.

Absolute Sustainability to Respect Our Planetary Boundaries

Taking a broader perspective on climate stability, Rockström, Steffen, and colleagues identified nine planetary environmental systems including the release of greenhouse gases to the atmosphere, use of land, and nutrient cycling. These are considered essential for the self-regulation of central planetary processes, ensuring the stable environmental conditions that we have known throughout the Holocene since last glaciation. Based on natural science, they propose for each system "safe operating spaces for humanity" delimited by critical impact levels ("Planetary boundaries") that we need to avoid exceeding in order not to jeopardise the stability of our natural systems. Out of the nine proposed planetary processes, they have proposed indicators for seven, and amongst these they find that the boundaries have been exceeded for three (Rockström et al. 2009; Steffen et al. 2015). While the work has inspired lively discussions of suitable indicators and concrete boundaries for all the individual planetary processes, the overall concept with its notion of absolute boundaries for environmental sustainability has inspired decision makers in governments (Nykvist et al. 2013) and industries (Science-based targets 2020; Ryberg et al. 2018b) to start benchmarking their activities according to absolute boundaries for environmental sustainability. For the latter case, absolute boundaries at the level of companies or even individual products have to be developed. They may be derived from science-based limits (like the planetary boundaries or ecosystem carrying capacities) for man-made environmental impact that defines a total pollution space that must not be exceeded (Bjørn et al. 2015; Bjørn and Hauschild 2015). Such a pollution space can be considered a restricted resource similar to the limited natural resources for which societal actors compete. Determination of which share of the space, an individual country or company can claim, requires an allocation of the total space. Assuming that the right to use the pollution space belongs to human individuals, the available space may be allocated amongst countries according to their population sizes as proposed by Nykvist and colleagues in their assessment of which nations stay within their share of the safe operating space delimited by the planetary boundaries (Nykvist et al. 2013) and by the Global Ecological Footprint Network in their calculation of ecological footprints for nations (Global Footprint Network 2020). Hjalsted and colleagues discuss the ethical implications of different approaches to allocating the space between industries and individual companies (Hjalsted et al. 2020), and Ryberg et al. test a number of allocation principles and demonstrate their influence on the absolute sustainability assessment of the service of laundry washing in Europe (Ryberg et al. 2018b). While there is some agreement about the principles for a science-based determination of the environmental limits and of a remaining pollution space, the allocation of the space between actors is in its infancy (Kara et al. 2018).

Engineering's Role for Sustainability

Standardised and Globalised Views on Sustainability

Engineering traditionally has had a strong focus on efficiency, aiming to maximise output or value creation while minimising input or costs. In an environmental sustainability perspective, efficiency may be expressed by an *eco*-efficiency of the activity, product, or provided service that is engineered. The International Organization for Standardization (ISO) defines eco-efficiency in the ISO 14045 standard as an "aspect of sustainability relating the environmental performance of a product system to its product system value" (ISO 14045 2012). Hauschild proposes the eco-efficiency defined accordingly as the ratio between the created value or fulfilled function for the product system on the one side and the environmental impact that is caused by the product system on the other side (Hauschild 2015):

$$\text{Eco-efficiency} = \frac{\text{Value created or functionality provided}}{\text{Environmental impact caused}} \tag{1}$$

The focus on increasing eco-efficiency promotes development of products and systems that offer more functionality per caused environmental impact or resource use. As a sidenote, however, we need also to be aware that the new products and systems created do not create newer, more difficult problems (e.g., shifting to smart systems to control energy usage, but where the smart system consists of increasing amounts of scarce and problematic materials) (Bihouix 2020).

In the context of the SDGs, the eco-efficiency can be seen as representing the balance between the SDGs related to human well-being (SDGs 1–5) and the SDGs representing the state of the environment (SDGs 13–15) (Fig. 3). The SDGs related to our prosperity and societal infrastructures (SDGs 6–12) represent the levers by which we can aim to increase the eco-efficiency – generating more well-being while causing less environmental damage and SDG 10 (reducing inequality) as a linking goal helps ensuring efficiency in the way human needs are met.

Fig. 3 The 17 SDGs and eco-efficiency (based on Richardson 2019)

The Sustainability Challenge to Engineers

The **IPAT equation** (Eq. 2) was developed based on the work by Ehrlich and Holdren (1971) and Commoner (1972). It analyses the environmental impact from human development and presents the total environmental impact (I) from human activities as the product of three central drivers – the human population (P), the affluence (A, the material standard of living), and a technology factor (T, representing the environmental intensity of our technology). T is expressed as environmental impact per created value or functionality and is hence the reciprocal of the eco-efficiency as defined in Eq. 1.

$$I = P \cdot A \cdot T \tag{2}$$

In a world where population and affluence grow, the technology factor or the environmental intensity of the technology with which we provide the growing affluence of the growing population must shrink, in order to avoid increased environmental impact. In some cases, the environmental impact is already exceeding sustainable levels as, e.g., demonstrated by the planetary boundary studies (Steffen et al. 2015) and acknowledged for climate change by many nations through their ratification of the Paris Agreement (UNFCCC 2020). This further exacerbates the need to reduce the environmental intensity of our technologies. But by how much must it be reduced? How big is the challenge that environmental sustainability of a growing consumption poses to our technology?

Considering that eco-efficiency is the inverse of the environmental intensity of technology, Eq. 2 shows us that an overall requirement to eco-efficiency can be described by the variables in the IPAT equation as:

$$\text{Eco} - \text{efficiency} = \frac{1}{T} = \frac{P \cdot A}{I} \tag{3}$$

In order to follow the Paris Agreement and limit temperature increases to the level of 1.5 degrees, reductions of around 45% in the 2010 emissions of CO_2 are needed by 2030 and around 2050 reductions must reach 100% (IPCC 2018). Considering forecast increases in population and affluence in the same period, this corresponds to eco-efficiency increases for climate change impact by a factor of 3 between 2020 and 2030. Indeed, the need for eco-efficiency increase by factors of 4, 10, 20, or even 50 have previously been proposed, for different types of environmental impact, over different time horizons and with different assumptions about developments in population and affluence (Factor 10 Club 1994; Von Weizsäcker et al. 1998; Reijnders 1998; Brezet et al. 1999; Schmidt-Bleek 2008).

These requirements to eco-efficiency improvements are derived from an assumption that A and T are independent, i.e., that increase in affluence is unaffected by developments in the eco-efficiency of the technology that supports the consumption. Unfortunately, this is rarely the case, as can be illustrated by the case of lighting technology. Over the last three centuries, we have witnessed energy-efficiency increases of lighting technology (from candles all the way to LED lamps) in the order of three orders of magnitude (Ausubel and Marchetti 1997), while over the same period, the share of our available income that we spend on lighting has remained constant (Tsao et al. 2010) (in spite of the fact that the available income has also grown strongly over this period). Here, as in many other cases, increased eco-efficiency leads to a growth in use (Magee and Devezas 2017; Hertwich 2005). It is clear that a strong increase in the eco-efficiency of products and technologies is required to ensure a sustainable level of environmental impact when meeting the needs of a growing and more affluent population, but these examples show that a focus on eco-efficiency alone is insufficient to ensure a future sustainable consumption and production. We must analyse the overall outcome for a product or technology, from a systems perspective, and relate it to the share of the pollution space that it can claim in order to ensure that the improvement leads to solutions that are not just more sustainable than what they replace but sustainable in absolute terms – to move the focus of engineering beyond eco-efficiency to aim for eco-effectiveness (Hauschild 2015).

In order to address the rather daunting task to develop technical systems that enable development towards absolute sustainability, engineering skills are needed both in analysing the eco-efficiency of the technology and in designing technology that is eco-effective.

Taking a Life Cycle Perspective

The eco-efficiency of a technical system is the ratio between the value or functionality that it provides us and the environmental impact that it causes (Eq. 1). The functionality is intended and typically defined as target for the product development, while the environmental impact is normally unintended, an unwanted price for obtaining the functionality. But how is it determined?

There are two fundamental principles when we want to quantify the environmental impact of a product. The first principle is that we need to consider the product system that comprises the whole life cycle of the product, from the extraction of the resources that are used in the materials and components of the product, over the manufacturing of the product through its distribution, use, and maintenance to the

Fig. 4 A typical product or system life cycle (own figure)

end-of-life treatment with possible remanufacturing, recycling, or landfilling (see Fig. 4). The many processes that constitute the product system interact with the environment, extracting resources and discharging emissions and waste to air, water, and soil, and it is these exchanges between the product system and the surroundings that cause the environmental impacts of the product that we need to quantify in order to determine the eco-efficiency.

The second principle is that we need to consider all relevant environmental impacts created by the exchanges between the product system and the surroundings, from the global impacts (climate change and stratospheric ozone depletion), where the pollutants are so long-lived that they reach global distribution so the impact is independent on where the emission occurs, to the more regional and locally dependent impacts (acidification, photochemical ozone formation, airborne particle pollution, chemical toxicity to humans and ecosystems, use of land and water).

Life cycle engineering is the name given to the engineering of the whole product system (Hauschild et al. 2017). It targets the eco-efficiency, taking the entire life cycle into account and considering all relevant environmental impacts to arrive at realisations of the product and its life cycle that minimises the unwanted environmental impacts associated with achieving the desired functionality. Life cycle thinking is essential for developing more sustainable products and systems, but it is also important to be able to quantify the impacts, in order to focus the development on the parts of the product system that contribute most for each of the considered environmental impacts and to document and benchmark improvements.

The environmental impact of a product is assessed using **life cycle assessment**, LCA. With its coverage of the entire life cycle of the product, from cradle to grave, and its consideration of all relevant impacts that the product causes along its life cycle, LCA captures potential problem shifting between the different stages of the life cycle and between categories of environmental impact when the environmental sustainability of products or services is compared (Finnveden et al. 2009).

The development of the LCA methodology has mainly taken place over the past four decades. Initially, the emphasis was on the conceptual foundation and on the overarching principles, and they were laid down in the ISO standards (ISO 14040 2006; ISO 14044 2006). Later, they followed a strong focus on inventory data for the multitude of processes of the product system and impact assessment methods for the many categories of environmental impact that are covered in LCA targeting development of international scientific consensus on methodological recommendations (Hauschild et al. 2013).

LCA is the tool used to assess the environmental impacts associated with obtaining a service, a functionality (the ratio between the service and the environmental impacts was defined as the eco-efficiency in Eq. 1). The anchoring in the provided functionality and its holistic perspective allows it to be used for assessing not just a product (system) but also other types of systems and even organisations. From a starting point in product assessments, the use of LCA has thus expanded to cover many types of systems and even policies. From an initial focus on environmental impacts, it has also gradually expanded to cover the other sustainability dimensions, the social (Benoît and Mazijn 2009) and the economic, and their combination into what has been coined life cycle sustainability assessment, LCSA (Zamagni 2012).

A recent research effort of interest for the absolute sustainability perspective in life cycle engineering is the development of spatially differentiated impact assessment that allows taking regional variations in environmental sensitivity into account when assessing regional and local impacts like acidification, particle air pollution, environmental toxicity, water use, and land use (Hauschild and Huijbregts 2015). Apart from increasing the environmental relevance of the results of the impact assessment, the regionalisation also supports relating the impacts caused by the product to environmental boundaries or carrying capacities of the systems that are actually impacted by processes in the life cycle of the product (Bjørn et al. 2016).

Another important research effort in this respect has been the attempt to move LCA from just supporting relative comparisons ("is alternative A better than alternative B?") towards also supporting absolute assessments of environmental sustainability ("is any of the alternatives environmentally sustainable?"). Bjørn and Hauschild proposed introduction of the absolute sustainability perspective into

LCA via the normalisation of product impacts against the environmental space available for an average person (Bjørn and Hauschild 2015) while Ryberg and colleagues developed a life cycle impact assessment method based on the planetary concept (Ryberg et al. 2018a) and implemented it in the previously mentioned case study of laundry washing to assess which amongst a series of system changes and life cycle engineering activities could make the activity environmentally sustainable in absolute terms (Ryberg et al. 2018b).

Detailed guidelines for LCA comprise the Product and Organisational Environmental Footprints from the European Commission, building on the ISO standards (European Commission 2016). A comprehensive introduction to the generic methodology and its application within numerous application areas is offered by Hauschild et al. (2018).

What Is Design for Sustainability?

In recognition of the potential to affect the sustainability performance of products and systems, the discipline of **design for sustainability** has developed over recent decades (Pigosso et al. 2015). In both industry and academia, increasing focus has been placed on sustainability awareness in the product development process, supported by an ever-increasing catalogue of tools and methods towards sustainability enhancement (Issa et al. 2015). From a triple bottom line perspective, early contributions and examples (from the early 1990s) have focused on improving the environmental footprint, both in terms of assessing the environmental burden of the product or system and in terms of the design of environmentally improved solutions. **Ecodesign** is often the term used to describe such approaches. As the methodology developed and as a growing number of industrial examples of ecodesign implementation were shared, the dimensions of social and economic sustainability considerations have been added to the palette of approaches.

In their meta-review of ecodesign tools and methods, Pigosso et al. chart the development of the body of knowledge regarding design for sustainability support from 1990 to 2015 (Pigosso et al. 2015). They show that companies have increasingly integrated sustainability into their business activities, taking it from a generally passive and reactive stance in the beginning of the period, towards adoption of more preventive and proactive approaches towards the end.

Focus on Ecodesign

Ecodesign is a proactive approach, where environmental considerations are integrated into the design and development of products and systems. The aim of ecodesign is to achieve improved environmental performance of products and systems, throughout their life cycles. Ecodesign is built on the two fundamental principles, introduced earlier, namely, life cycle thinking and environmental impact reduction. This means that with ecodesign, considerations of raw material extraction, manufacturing, transport, use, and end of life are made, throughout the design and development processes of products and systems.

Hundreds of ecodesign tools and methods are available today (Pigosso et al. 2015; McAloone and Pigosso 2021). Many ecodesign tools are provided to support specific environmental decisions within specific parts of the development process (e.g., materials selection, energy source definition, mode of transport), whereas others help the designer to create a holistic ecodesign support, from the very first ideation of the product or system, all the way through detail design and to launch of production. To ensure success, ecodesign should build upon the foundation of an in-depth understanding of the product or system's actual or potential environmental impacts, typically by carrying out some form of (abridged or full) life cycle assessment (LCA). Ecodesign stimulates the designer to be innovative and creative in the development process, supporting the process of seeking alternative solutions, whether they be at the material, component, product, or systems level.

In addition to single tools and methods, various proposed processes or reference models for ecodesign also exist. One such proposal of a holistic ecodesign approach is provided by McAloone and Pigosso (McAloone and Pigosso 2021), who propose a reference model for the integration of ecodesign into product development. The reference model takes both the life cycle and the environmental impact principles into consideration and provides two ways of tackling an ecodesign task, namely, (i) a top-down, design-driven approach and (ii) a bottom-up, environmental life cycle approach; see Fig. 5. Given the integrated nature of modern companies, both viewpoints are essential to understand. In some circumstances, a company may desire to design a complete system from an ecodesign perspective, keeping all environmental improvement options and eventualities open. In other circumstances, punctual environmental improvements may be necessary, for which the bottom-up approach is more suitable. Figure 5 displays the ecodesign reference model provided by McAloone and Pigosso.

Reflecting the development of industry's capabilities regarding the integration of ecodesign into their business, the international standard on environmental management systems, ISO 14001, has augmented its guidance and expectations in the latest release of the standard (2015). The updated standard requires that the overall ecodesign process and approach should be detailed, within any company with product development activities wishing to renew its certification from 2015 onward (ISO 2015).

From Ecodesign to Design for Sustainability

As industry has developed its understanding and expertise within ecodesign, so has the need to integrate economic (business) and social considerations into the development process for products and systems. Many companies have developed over the past decade or so, from considering corporate social responsibility (CSR) as a chiefly reporting initiative (Tu et al. 2013) to now aiming to fully integrate social sustainability and social innovation into their core business, from strategy all the way down to deployment within product development (Chang 2015; Kim et al. 2015). Such a broadened understanding

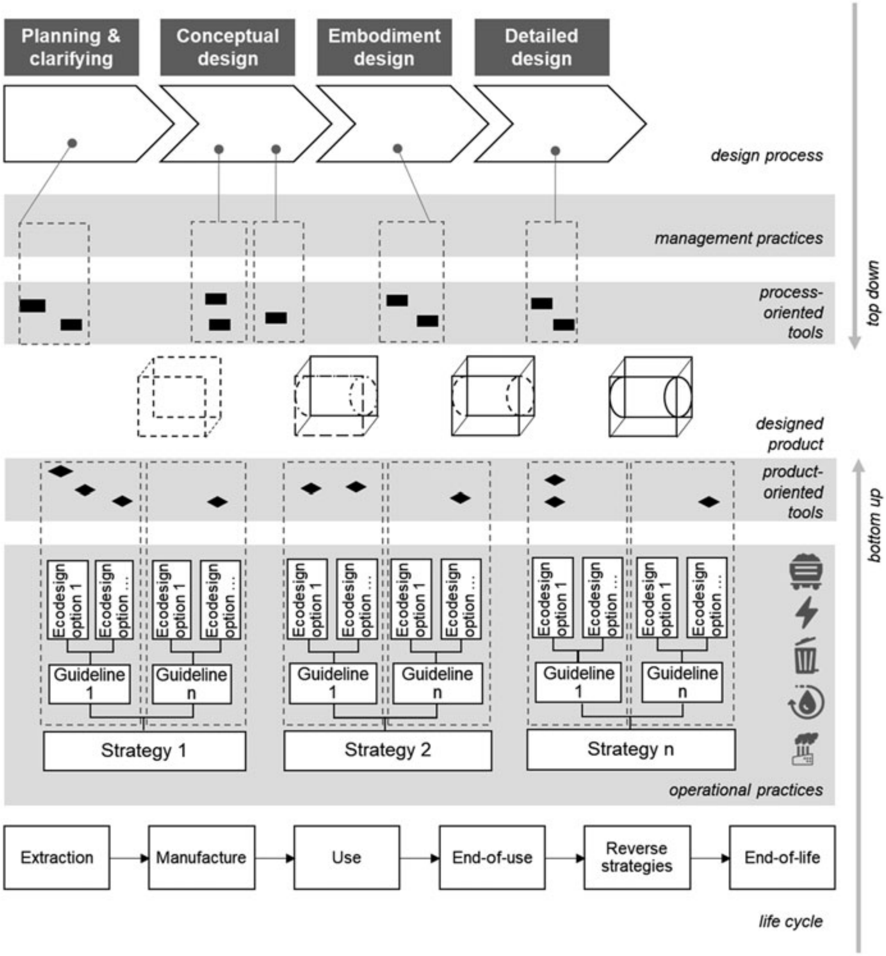

Fig. 5 Ecodesign reference model, displaying top-down (design process) and bottom-up (environmental life cycle) perspectives (McAloone and Pigosso 2021)

and intention regarding sustainability within business lead to a need to significantly augment the support through frameworks and tools. Companies today are working to understand how to integrate the goals and measures provided by the 17 earlier-mentioned UN Sustainable Development Goals, into their business and product development processes (Mascarenhas et al. 2020; Park et al. 2017; Stead 2019). Thus, an increasingly holistic view on sustainability in business and product development requires a systems view and the development of comprehensive tools to evaluate the sustainability performance of products. There is a clear trend towards the development of unified tools that can measure the sustainability performance of products considering the environmental, social, and economic dimensions (Roostaie et al. 2019).

An Engineering Systems Perspective on Sustainability

As mentioned in the introduction to this section on Design for Sustainability, the body of knowledge in this field has been developing now since the early 1990s, both through scientific research efforts and bold, early-mover companies (Pigosso et al. 2015). Yet, only within recent years, after almost three decades of effort, do we see emerging maturity in the way in which companies integrate sustainability into their businesses, with regard to product-related organisations. Adding “sustainability” to not only the requirement specification but into the product development processes, company governance systems and the designer’s toolbox seem not to have been that easy to achieve – and here we are still considering a product level. Augmenting our scope to complex and large-scale socio-technical engineering systems is a next step that is relatively uncharted in the literature. Cluzel et al. provide the most convincing contributions to ecodesign of complex industrial systems, with reference to large electricity conversation stations (Cluzel et al. 2016). In addition, Tchertchian and Millet provide some insights into providing life cycle screening as a support to the consideration of sustainable complex systems design, with a maritime case as an example (Tchertchian and Millet 2017). There are more studies and methodologies to support the full life cycle assessment (LCA) of complex systems (e.g., Wang and Shen 2013), but LCA alone is not enough to support the process of socio-technical design. The good news is that many of the principles, methods, and tools from sustainable product design can be used for sustainable engineering systems design. The scope broadens and the causalities between decisions become, by nature, more complex. What does not yet exist is a process or number of proposed processes towards sustainable complex engineering systems design.

Why an Engineering Systems Approach to Sustainability?

Continuing the story of how companies have developed their understanding, and therefore also their business activities, from passive/reactive approaches to sustainability through to preventive/proactive approaches, the current era of sustainability leadership in industry is seeing integrative approaches to sustainability. This includes active adoption of environmental, social, and business-related sustainability goals into company strategies and further deployment into numerous parts of the organisation. Two significant agendas stand out as being of particular interest for companies, as they seek to “do more good” as well as “do less bad”, as the adage regarding complementary approaches to sustainability states (Toxopeus et al. 2015). The two agendas are **product as a service** (or product/service-systems, PSS) and **circularity** (or circular economy, CE). Both agendas are supported by the basic premise that the necessary improvements in global sustainability performance to just maintain status quo in our ecosystem need to reach up to a factor 20 in performance improvement (Reijnders 1998; Brezet et al. 1999) and that single-product, transactional sale, linear economic thinking lies at the core of the problem of industrial production and modern-day consumption.

Product as a Service

Product as a service (referred to in academic literature as product/service systems, or PSS) emerged in the early 2000s and has grown strongly in society, in recent years. From a sustainability perspective, the emergence of PSS as a scientific research theme was motivated by the ambition of finding alternative ways of contributing to the projected factor 20 need (Roy 2000). The basic hypothesis was that by combining the physical artefact and the service that the product provides to the user as design objects – and as combined offerings to the user – greater sustainability improvement potential can be realised. In such cases, the company retains (greater degrees of) ownership of the physical artefact and adds a responsibility and influence upon the sustainability performance of the product throughout its lifetime. From a technology perspective, the dawn of fast and wide-coverage Internet, smartphone technology, and smart sensory devices and actuators (also known as Internet of Things, or IoT) has seen the availability of PSS solutions that hitherto were not possible to provide. Car-sharing systems rely on electronic door locks, actuated by smartphone apps. Pay-per-use photocopy machines depend on login and counter technology. And home delivery of ecological fruit and vegetables relies on fully integrated, web-based order systems, connected to complex logistics setups. The most famous ontology of PSS types comes from Tukker (2004), who describes eight PSS solution types, ranging on a scale from straight product offerings to straight service offerings. Tukker's work was also motivated from a sustainability background, in an attempt to find a route to decoupling of consumption from production.

It is an ideal of the development of PSS that the three main stakeholder groups – customer, provider of the service, and society – must benefit from the service systems through their product-as-a-service solutions and that value creation is decoupled from production and consumption of multiple products. However, like all things, there is neither a one-to-one correlation nor a guarantee of increased sustainability performance, simply due to a switch to PSS (Pagoropoulos et al. 2018), and there are even examples of a more negative sustainability performance through PSS solutions (Barquet et al. 2016). PSS merely opens up the solution space and the sphere of influence, due to reconfigured responsibilities and motivations; the remainder of the task of achieving sustainability improvements is still up to the provider to ensure. Thus, the task becomes more complex and requires more careful insight and consideration.

Circularity

Circular economy, CE, has become widely recognised in a very short time, as being of key potential in promoting and achieving a better balance, from a material and resource perspective, within modern society. The design of innovative circular business models, together with circular product and service solutions, is accepted as being critical, with the potential of affecting fundamental changes to the resource consumption that the linear economy has been responsible for.

The notion of circularity may not be new to you. Anyone with family members who were alive in the middle of the twentieth century will, for example, tell stories of how every product, every material, and every item of clothing was saved for a second, third, or fourth usage, including necessary repurposing along the way. And there are parts of the world where frugality gives rise to circularity, at local and personal levels, still today. The difference with the current focus on circular economy is that an attempt is being made to apply ***circularity at a systemic level***, and in times of economic growth, as opposed to depressed economic necessity.

From a product and engineering systems design perspective, this latest development along the trend of positive attention to ecodesign and sustainability by companies is marked by the successful campaigns of "cradle-to-cradle" and "circular economy", respectively.

The "cradle-to-cradle" concept was first launched in 2002 by Braungart and McDonough and gradually reached considerable industry attention towards the early 2010s (McDonough and Braungart 2010). "Cradle-to-cradle" challenged the industry's dominating linear mindsets of "cradle-to-gate" (from raw material, through production, to the factory gate) or "cradle-to-grave" (from raw material, through production, sales, and use, to final depositing of the waste stream – the grave). Instead the authors proposed a new way of thinking in a cyclical manner. One cradle-to-cradle dictum is "waste equals food", reflecting the overarching philosophy behind the concept that we should learn from and mimic nature in our engineered world. Nature is thus not *efficient* (as engineers are trained to be); rather it is *effective* (meaning that it has evolved in an adaptive manner so waste of the right type is of value in another product or system's life cycle). To make this philosophy operational, the cradle-to-cradle methodology is based on principles for ***materials health*** (toxic materials and incompatible combinations of materials must be avoided), ***material reutilisation*** (enabling recovery and recycling of all materials at the end of life of the product), use of ***renewable energy*** (focused on the production, not the use stage of the product), and ***water preservation*** (particularly usage and discharge quality). The "closed loop" approach to the product life cycle that is advocated in cradle-to-cradle is split into a "technical cycle" and a "biological cycle" view on product and system flows according to the nature of the materials.

The renascent "circular economy" builds on top of and has found inspiration in the cradle-to-cradle concept and broadened the perspective from a strong materials chemistry focus to advocating for sound business thinking about how to maximise value output while minimising the production, consumption, and wasting of material goods. This thinking has in particular been championed by the Ellen MacArthur Foundation (Ellen MacArthur Foundation et al. 2015), and it has now been broadly adopted and reinforced by scholars, industry practitioners, politicians, and interest organisations, as a promising means to achieving a better balance, regarding resource consumption and production. The circular economy thinking is reaching industries and public societies across the globe. For companies, it is supporting sustainability becoming an integral part of their way of doing business, introducing changes in their business models and how they deliver value, by means of the previously mentioned product/service systems (Kjaer et al. 2019).

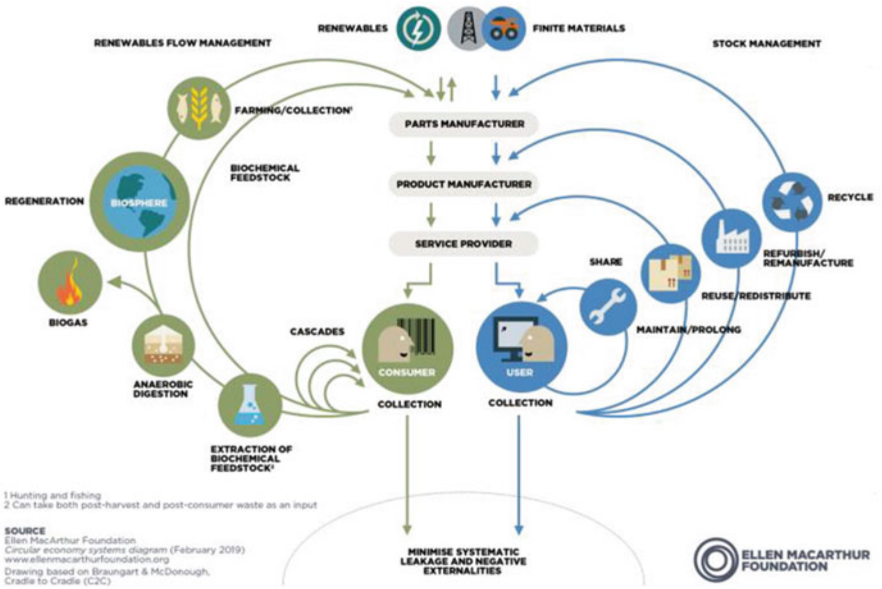

Fig. 6 Butterfly diagram by EMF (2019), based on McDonough and Braungart (2010)

At the time of writing, the full picture of the circular economy life cycle model is still being drawn, through various contributors' additions to this new lens on sustainability. The currently most dominant model is the so-called Butterfly Diagram, provided by the Ellen MacArthur Foundation (Ellen MacArthur Foundation et al. 2015) showing a number of secondary flows in both the technological and biological cycles.

Although focused on eco-efficiency rather than eco-effectiveness, many of the existing ecodesign tools are fully useable and relevant for developing also cradle-to-cradle-inspired designs or products that are designed to play a role in a circular economy. In its simple and recognisable schematic, Fig. 6's butterfly diagram depicts a number of alternative routes for material resources, to divert from the linear model of "take-make-use-waste". Closer consideration of each alternative route (the arrows) for material resources brings us to an understanding that the panacea of achieving circularity requires consideration of not just artefacts but also policy, business model, design, logistics, and a host of other considerations. A large number of circular strategies have been developed and ordered, to help to consider circularity (Blomsma et al. 2019). And numerous resources emerge, supporting the value chain considerations to be made when attempting to design for and operate within a circular economy (Kalmykova et al. 2018).

Transitioning to Circular Economy

But how to make the change, from our linear system to a circular economy? According to economist, Tim Jackson, it is important to not only question how to decouple wealth creation (Jackson 2009) (often measured in economic growth) from resource consumption, which can be argued as being the main aim of both circular economy and SDG 12. Jackson's career has been dedicated to prompting us to question the whole notion of economic growth – at least in developed economies. It seems that the only way to truly reach a circular economy is to create . . . a new economy!

Steps towards circular economy, however, can be taken. Transitioning to circular economy is not just about changing the product/system design or beginning to recycle products, component, and materials. It is also about transitioning the organisation; innovating the company strategy and business model; redesigning the system, product, or service for circularity; assessing and adjusting manufacturing processes and value chain considerations; interpreting and employing technology and data to ensure system health and longevity; understanding how better to support engineering systems through maintenance; being able to make informed choices about take-back and end-of-life strategies; and understanding the policy and market conditions for circular economy (Pigosso and McAloone 2021). Understanding and acting on readiness within all of these dimensions will ensure a holistic systems approach to circular economy transition. Or in other words, we can only expect to make a circular economy a reality, if we take a systems perspective to the multitude of dimensions listed above.

The ultimate goal with circular economy is to reach "an industrial economy that is restorative or regenerative by intention and design", as defined by Ellen MacArthur Foundation (2013). Restorative entails a circuit of infinite use, reuse, and repair. Regenerative refers to a cycle of life that maintains and upgrades conditions of ecosystem functionality (Morseletto 2020). The design of engineering systems plays, therefore, a key role in achieving restorative and regenerative systems.

The Contribution of Engineering Systems to Sustainability

Both product as a service or product/service systems (PSS) and circular economy represent considerable complexities, in comparison to the single-product, single life cycle, transactional world view. Vast amounts of research are being carried out in both areas, both of which are in need of support regarding how to design and develop, how to implement and operate, and how to assess the sustainability performance of circular PSS solutions. As the knowledge on circular economy develops, it is also becoming clear that PSS is a means to circular economy and circular economy is, in turn, a means to sustainability. Neither are *the* sole means, but this supporting and causal relationship makes the role of each approach clearer.

It also becomes clear when one begins to talk of product/service systems, of multiple life cycles, and of materials and waste hierarchies that the potential of an engineering systems approach begins to manifest itself clearly. In this context, it is important to embrace the "sciences of complexity" required to address ever-increasing "wicked" problems (Broadbent 2004) within complex socio-technical systems through the understanding of the complex dynamics of economic, environmental, and social factors in sustainable design, across the system life cycle (Fiksel 2003). Furthermore, there is a need to expand the role of the design process as a powerful leverage point at which to intervene in production and consumption systems (Sterman 2002), despite the increased recognition that wider-scale systemic changes can be addressed by design (Gaziulusoy and Brezet 2015) of engineering systems.

Conclusions

This chapter has provided a brief insight into the history, key terms, important considerations, and possible future role of engineering systems with respect to sustainability. Not all the answers are provided – indeed there are gaps to be filled and knowledge to be generated, in order to develop a comprehensive support for how engineering systems can make a contribution to sustainability through socio-technical engineering systems design. The key takeaways from this chapter are as follows.

- The current sustainability emergency has been created by humans and cannot be fully fixed by technology alone, or by looking at discrete activities, products, companies, or technologies.

  Sustainability is a socio-technical challenge that requires holistic socio-technical design solutions.
- Our understanding of sustainability, over the past five decades, has developed. Increasingly, we need to think in terms of absolute sustainability, which will imply setting limits for how "much is enough and acceptable".

  Absolute sustainability will become an instrument of future engineering systems.
- To aid our approach to designing engineering systems for sustainability, it is important to understand the life cycle, in order to assess the environmental performance of the engineering system under consideration.

  Life cycle assessment is an important instrument to enable the dimensioning of sustainable engineering systems.
- Design for sustainability is a well-established discipline, with many potentially useful methods and tools to enable sustainable engineering systems, but there is limited material on actual process support to aid the design of sustainable engineering systems.

  There is a need to create design support for sustainable engineering systems.
- Engineering systems as a discipline should be able to contribute to sustainable product/service-system design and to circular economy. Both require a systems perspective to succeed. Both constitute part of a causal chain to an attempt to achieve sustainability, such that PSS contributes to the goal of reaching a circular economy and circular economy contributes to the goal of sustainability.

  PSS and circular economy – which both have the potential to contribute to sustainability – require a systems approach, which could be provided by an engineering systems design approach.

We hope that this chapter can provide the basis for a sustainability goal, when reading the other subsequent chapters in this handbook.

Cross-References

- ▶ Formulating Engineering Systems Requirements
- ▶ Introducing Engineering Systems Design: A New Engineering Perspective on the Challenges of Our Times
- ▶ Properties of Engineering Systems
- ▶ Systems Thinking: Practical Insights on Systems-Led Design in Socio-Technical Engineering Systems
- ▶ Transitioning to Sustainable Engineering Systems

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Digitalisation of Society

6

Dieter Spath, Jürgen Gausemeier, Roman Dumitrescu, Johannes Winter, Steffen Steglich, and M. Drewel

Contents

Abstract

While the term digitisation mainly refers to implications of digital technologies, digitalisation covers also the changes in society. It opens up fascinating possibilities and will change the world of tomorrow. It is important to tap the associated potentials for innovation in order to maintain competitiveness and secure future

D. Spath
acatech - Deutsche Akademie der Technikwissenschaften. National Academy for Science and Engineering, Munich, Germany

Institute of Human Factors and Technology Management (IAT), University of Stuttgart, Stuttgart, Germany
e-mail: spath@acatech.de

J. Gausemeier · M. Drewel
Heinz Nixdorf Institut, Universität Paderborn, Paderborn, Germany
e-mail: juergen.gausemeier@hni.uni-paderborn.de; marvin.drewel@miele.com

R. Dumitrescu
Fraunhofer-Institut für Entwurfstechnik Mechatronik IEM, Paderborn, Germany

J. Winter · S. Steglich (✉)
acatech - Deutsche Akademie der Technikwissenschaften. National Academy for Science and Engineering, Munich, Germany
e-mail: winter@acatech.de; steglich@acatech.de

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success. However, studies show that many companies still have major problems in shaping the digital transformation. The sometimes disruptive character of digitalisation is already impressively evident in retail (e.g., Amazon), television (e.g., Netflix), or the travel industry (e.g., Airbnb). But a fundamental change is also emerging in industrial sectors such as mechanical engineering or automotive industry, which is expressed by the popular term Industry 4.0 (Kagermann and Winter. The second wave of digitalisation: Germany's chance. In: Messner D, Mair S, Meyer L, (eds) Germany and the World 2030. What will change. How we must act. Econ Publ, Berlin, 2018). This will have a significant impact on the design of tomorrow's engineering systems (de Weck et al. Engineering systems: meeting human needs in a complex technological world. MIT Press, Cambridge, 2011). Those socio-technical systems increasingly shape the economy but also other fields of society such as law, ethics, security, work, and ecology. The described challenges make it necessary to structure the field of action of digitisation. We use a framework consisting of three fields of action: (1) products and services, (2) value creation, and (3) business models. For each field we will discuss the effects on industries as well as societies.

Keywords

Business model · Digitalisation · Digitisation · Engineering systems · Engineering systems design · Products and services · Society · Value creation

Introduction

Digitalisation is a megatrend of the twenty-first century (Horx et al. 2007). The term is used "in a rare and never before experienced accumulation" (Mertens et al. 2017). It refers to the changes in society, which are caused by the implications of digital technologies. Despite all the hype, digitalisation is not a new trend. The third industrial revolution began at the beginning of the 1970s and continues until today. It is characterised by the use of electronics and IT in businesses around the world and the progressive standardisation and automation of business processes. The technological digitisation is driven by the exponential growth of several performance parameters, processors, data memory, and networks, as described by Moore's law. Exponential growth is typical for the IT industry, but hardly for traditional industries or societies. For a long time, the effects were barely noticeable. As a result, numerous actors from business, politics, and society have classified digitalisation as uninteresting and underestimated its long-term effects. Once these long-term effects became self-evident, politicians and managers recognised that it is often no longer possible to keep up. Electronics and IT drove the automation of production and lead to often dramatic structural changes in value chains, employment structures, and products and services. All business processes such as orders, invoices, and flows of products or payments were documented by paper documents. Nowadays paper documents are given a digital twin, i.e., a virtual image. These digital twins are now connected within a company's IT system and processed in almost real time. Standardisation and automation have made business processes more efficient, faster, and more transparent (Kagermann and Winter 2018).

Back in the year 2000, when the dotcom bubble burst, there was already the example of the beverage vending machine, which ordered replenishment on its own. In search of promising business models for the age of digitalisation, electronic marketplaces were broadly discussed as pioneers for dynamic business networks and real-time business. Many of the technology companies that are on everyone's minds today were already on the market back then, such as Google, Amazon, Netflix, or the predecessors of Facebook. For some years now, we have been experiencing a second wave of digital transformation and a Fourth Industrial Revolution. The necessary information and communication technologies are now so cost-effective that they can be used across the board. As a result, many of the dotcom promises are becoming reality today. At the same time, there are new aspects of digitalisation that go far beyond the ideas of the last big hype. We can use the words smart, networked, or autonomous to describe these new ideas. Smart means that almost every object can be digitally connected and networked. Now not only the paper documents, but all physical objects are given a digital twin. Machines, production plants, vehicles, or even household appliances with embedded electronics are networked via the Internet. Real and virtual worlds merge to form cyber-physical systems. The result is an Internet of Things (IoT) that penetrates all areas of work and life. The collection and use of data becomes omnipresent. Autonomous systems use artificial intelligence (AI) to make independent decisions, also on the basis of their own learning processes (Kagermann and Winter 2018).

Despite all the euphoria, it must not be overlooked that the introduction and use of IT systems is at the end of a well-considered chain of action and not at the beginning. Figure 1 illustrates the four stages of an ideal chain of action (Gausemeier et al. 2014).

1. **Forecast**: This level is about anticipating the developments of markets, technologies, and business environments in order to recognise the opportunities of tomorrow, but also the threats to today's established business at an early stage.
2. **Strategies**: Business, product, and technology strategies must be developed at this level in order to take advantage of the opportunities of tomorrow.
3. **Processes**: (Business) processes at this level must be designed in such a way that they optimally support the chosen strategies.
4. **IT systems**: At this level, well-structured (business) processes must be supported by IT systems.

As indicated in Fig. 1, the technological digitisation primarily addresses the IT system level. Before activities and investments take place here, the questions shown in the figure need to be answered with reference to the three superordinate levels. Only when these questions have been answered, digital solutions have a chance of success.

While the term digitisation mainly refers to the abovementioned technological implications of digital technologies, there are also other concepts, each of which provides a framework for introducing IT innovations and their effects. As a structured literature review shows, there are three relevant concepts (Bockshecker et al.

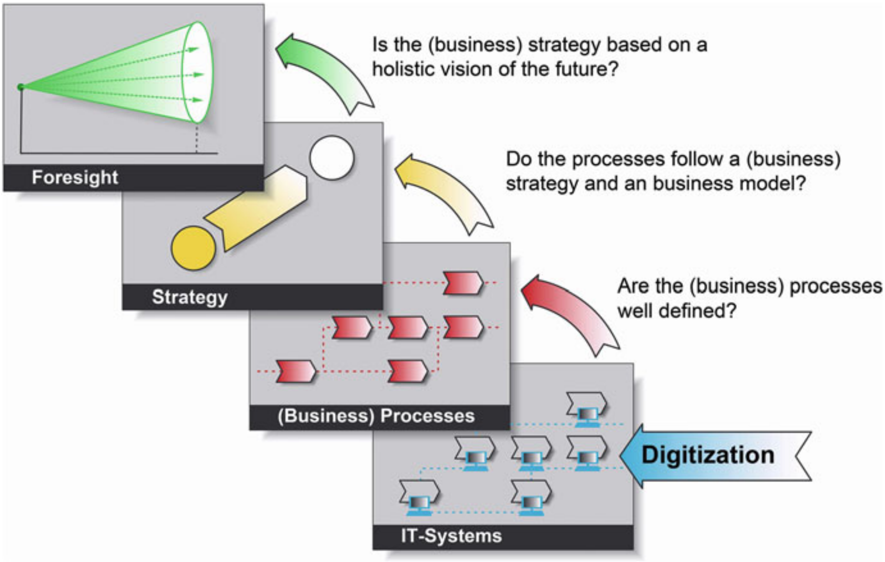

Fig. 1 The four-level model for future-oriented corporate design

2018): digitisation, digitalisation, and digital transformation. The term *digitisation* focuses on the abovementioned technological implications of digital technologies. From this technical point of view, the term digitisation refers to the conversion of analogue data into digital data (Mertens et al. 2017; Bleicher and Stanley 2016). Digital data is "information presented in an agreed and machine-interpretable form", which consists of a limited character set and is discrete in time and value (Schöne 1984). By contrast, analog data is represented through continuous functions of physical quantities, which are continuous in time and value (Lassmann 2006). This perspective on technology, however, often neglects "all changes and their results in all parts of human society that result from the increased use of digital technologies" (Eckert 2014). While digitisation is allocated with the technical systems, the approach of *digitalisation* usually comprises the social as well as the technical system (Bockshecker et al. 2018). Digitalisation entails a variety of changes, amongst others, for organisations (Andersen and Ross 2016), business models (Brenner et al. 2014), or the way people work (Abel et al. 2019). *Digital transformation* does not only take social and technical aspects into account but also emphasises the process of organisational or societal changes based on digitalisation (Bockshecker et al. 2018; Schallmo et al. 2018).

In this chapter, we also take this more comprehensive point of view and illustrate the impacts on society which go beyond technical changes. The advantage of the concept of digitalisation is that it addresses the increasing necessity for engineers to consider the effects of new innovations on users and different areas of society, such as law, ethics, security, work, and ecology. Especially companies and business consultancies usually focus solely on technical aspects or alternatively only on social aspects directly linked to organisations (IBM 2011; PWC 2016). In contrast, the perspective on digital transformation broadens the view of this analysis even further. We will consider these aspects especially in the section "Societal Challenges and Opportunities of Digitalisation". Therefore, we understand the digitisation of engineering systems, such as products, services, value chains, etc., as the digitalisation of complex socio-technical systems. Those engineering systems have the potential to fulfil important functions in society and can meet central economic and social challenges (de Weck et al. 2011).

This chapter focuses on innovations made possible by the technological digitisation. The fields of digitisation are shown in Fig. 2. Accordingly, the following dimensions of digitisation are distinguished (Echterfeld and Gausemeier 2018):

1. **Digitisation of products and services**: Contains product innovations based on digital technologies, e.g., autonomously driving cars, service innovations realised through the use of digital technologies, e.g., predictive maintenance for machines and engineering systems
2. **Digitisation of value creation**: Production innovations based on digital technologies, e.g., Plug and Produce for machines and plants or process innovations using digital technologies, e.g., Robot Process Automation (RPA)
3. **Digitisation of business models**: Business model innovations made possible by digital technologies, e.g., performance-based contracting

Within the following sections, we will describe for each field of action how it will be changed by digitisation and which effects the changes will have on society. Digital technologies enable these changes. According to Stähler, digital technologies

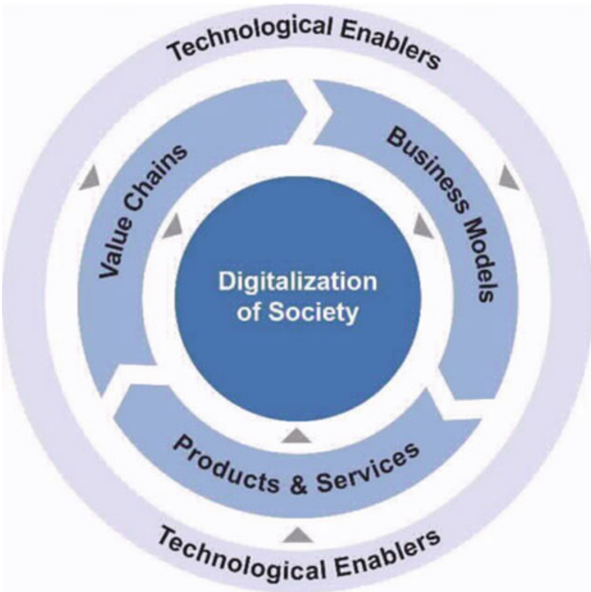

Fig. 2 Fields of action of digitisation

are those technologies that "support the collection, linking, processing, storage, presentation or transmission of data and information" (Stähler 2002). The consequences of these changes can be disruptive. However, they will often also trigger incremental improvements in (sub-)systems. In the following sections, we will discuss both disruptive and incremental changes.

Digitisation of Products and Services

The disrupting force of digitisation can already be witnessed in numerous industries. Examples range from the retail sector (e.g., Amazon) to the media and entertainment industry (e.g., Spotify, Netflix) through to the hospitality and travel business (e.g., Airbnb). In all these industries, incumbents were overturned. Markets were reshaped by digital solutions and changed consumer behaviour. But also in business-to-business industries like machinery and plant engineering or electronics, a fundamental digital change is currently unfolding, which is expressed by popular terms like smart products, Internet of Things, or Industry 4.0 (Kagermann et al. 2013). Bradley et al. employ the metaphor of a digital vortex to describe the inevitable convergence of all industries towards a digital centre in which offerings are digitised to the maximum extent possible. The speed with which the industries converge to the vortex' centre naturally differ – e.g., digital transformation in retail sector obviously has progressed very much further than in machinery and plant engineering industry. However, at the end of the day, no enterprise can evade the digital changes in its specific business environment (Bradley et al. 2015). Figure 3 shows an example for

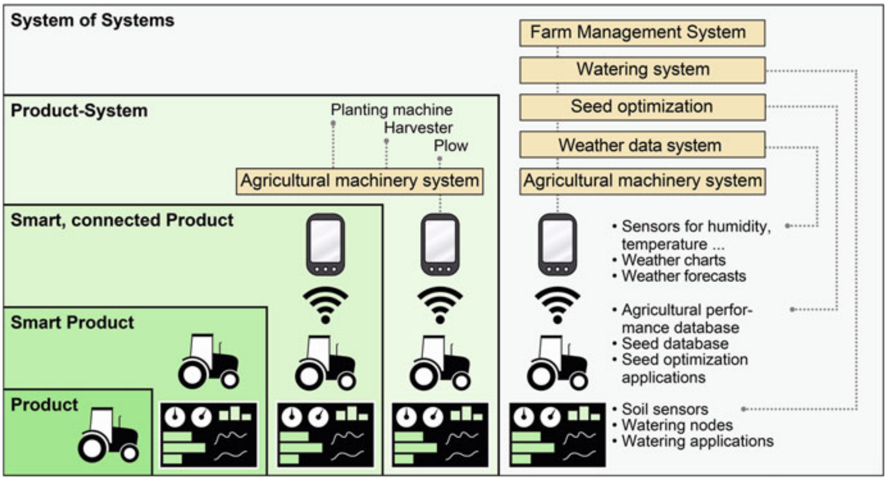

Fig. 3 Development of classical agricultural machines towards system of systems (Porter and Heppelmann 2014)

the ongoing digitisation process. Due to the constant increase of digital technologies within agricultural products and their cross-linking, the agricultural machine has developed over the past few years from a classical product into a so-called system of systems.

Even if this figure, according to Porter and Heppelmann (2014), illustrates digitisation very well, it does not represent the digitalisation of social systems in particular. Engineering systems in the agricultural sector like in all the other sectors are socio-technical systems and affect further systems in their environment such as other socio-technical systems of systems, communication systems, energy systems, legal regulations, or the ecology.

However, the abovementioned example also shows that Zuboff's law which essentially states that everything that can be digitised will be digitised has never been more relevant than today (Zuboff 1988). In order to survive in the digital age, companies have to innovate their product and service portfolio. Many companies have already recognised this necessity and have started to digitise their products and services by equipping them with information and communication technologies and connecting them via the Internet. Figure 4 shows four examples in which enterprises from different industries have innovated their products by adding new digital features: The tire manufacturer Hankook has developed an intelligent tire which is able to brake automatically in case of ice or aquaplaning. Moreover, it can vary its air pressure depending on the street conditions to enhance traction and rolling

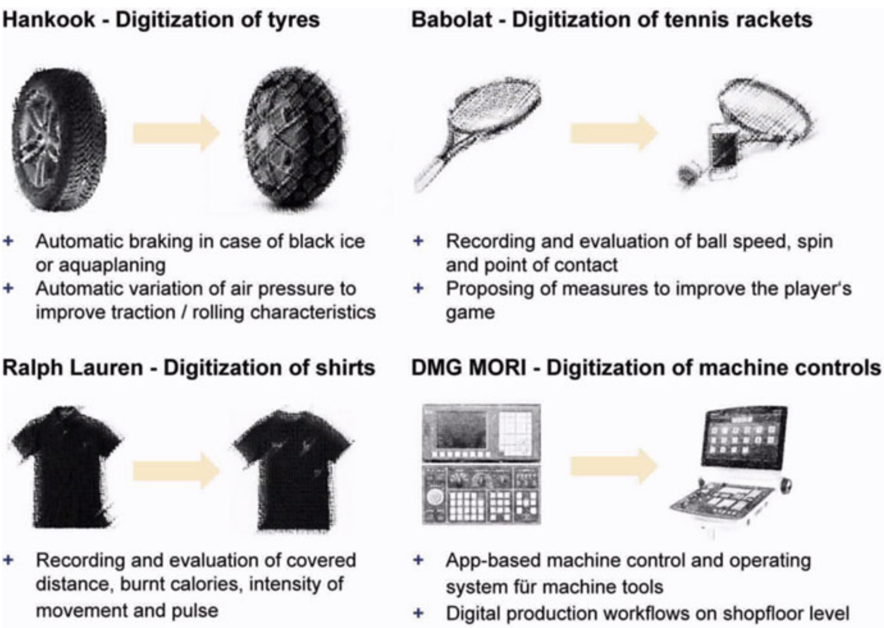

Fig. 4 Examples for digitised products (Echterfeld and Gausemeier 2017)

characteristics (Noll et al. 2016). The tennis outfitter Babolat integrated sensors and networking components into the grip of its tennis rackets which make it possible to record and evaluate the ball speed, spin, and point of contact. In this way, players are supported in systematically improving their game by a smartphone app. The fashion manufacturer Ralph Lauren recently brought a sports shirt to the market which is able to record and evaluate an athlete's covered distance, burnt calories, intensity of movement, and pulse (Porter and Heppelmann 2014). Last but not least, the machine tool manufacturer DMG MORI developed an app-based machine control and operating system which also provides digital production workflows on the shop floor.

The extensive changes in the product world can also be expressed in figures: A study conducted by the business consultancy PwC predicts that the share of highly digitised products will almost triple until the end of 2020. This will lead to an expected increase in revenues of nearly 2.5% per year (Koch et al. 2014). A survey conducted by the German Association for Information Technology, Telecommunications and New Media (BITKOM) reveals that 40% of the companies interviewed plan on digitising their product portfolio within the next years (Dirks 2017).

The products of the digital age are manifold and are characterised by different degrees of digitisation (Clement and Schreiber 2013). In this context, Noll et al. speak of a continuum of products that is spanned by the two extremes "physical products" and "digital products" (Fig. 5) (Noll et al. 2016). "Physical products" are physical and have no digital content. An example is mechanical-centred systems. "Digital products", on the other hand, are intangible and purely digital. This type of product includes, for example, application software (Stelzer 2004).

A large proportion of today's products have both physical and digital components and move between the two extremes depending on the dominant share. These products are often referred to as "digitals" (Rigby and Tager 2014) or "digitised products" (Appelfeller and Feldmann 2018) and can be considered as engineering systems. Both the examples and the figures show that digitised products will have an ongoing massive impact on tomorrow's global innovation landscape and therefore also on various fields of society such as mobility, work, or leisure. For companies, it will therefore be crucial to bring out a continuous stream of digital product innovations to defend or even strengthen their competitive position and ensure future business success (Porter and Heppelmann 2015).

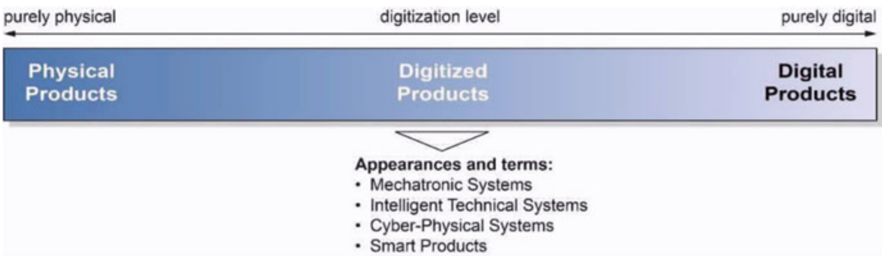

Fig. 5 Continuum of products in the digital age (Noll et al. 2016)

Medical technology as an example for the digitalisation of society: Digital products and services in the field of medical technology are becoming increasingly important for the healthcare system. New possibilities arise to improve operations and interventional procedures. Further goals are the improvement of treatment quality as well as the reduction of complications and hospital stays. In addition, digitalisation improves the generation, networking, and evaluation of medical data. In this way, medical technology products help to achieve the overall goal to customise the healthcare system to the individual requirements of individual patients (acatech 2017). An example of digital products are semi-autonomous and robotic systems as assistance for operations. The degree of automation varies from the specification of a virtual geometric boundary to the complete automation of a work step. This allows a higher precision and better adaptation to the individual needs of the patient. However, the acceptance of these devices by users and patients is still too low to fully exploit their potential. All in all, there are still many questions to be answered in the field of medical technology. Medical devices such as prostheses and implants are generating more and more personal data that must be merged and evaluated without violating data protection. In addition, the new technology raises ethical questions, such as the increasing possibilities of manipulating the brain. Another aspect is the regulation of medical devices with regard to certification and benefit assessment, which is becoming more complex and therefore involves greater effort and risk for manufacturers (acatech 2017).

Digitisation of Value Creation

With digitised value creation, companies can cost-effectively manufacture individual products, increase resource efficiency, shorten throughput times, and identify and control disruptive factors at an early stage. Digitisation is finding its way into both the horizontal and vertical value chains (Kagermann et al. 2013; Koch et al. 2014) (Fig. 6).

Horizontal: Digitisation of the horizontal value chain integrates and optimises the flow of information and goods between suppliers, cooperation partners, customers, and the company itself. All areas of a company (e.g., purchasing, production, logistics) as well as all external partners that are required to provide a product are connected and managed with foresight. Cooperation partners are gaining importance, since in the digital age no company alone has the necessary know-how to be successful in long term. At the centre of the horizontal digitisation of value creation is the networking of autonomous production and transport resources, including their planning systems. All machines provide their data, which can be specifically requested by the resulting products. Machine-to-machine communication with active digital product memories turns the product into an information carrier,

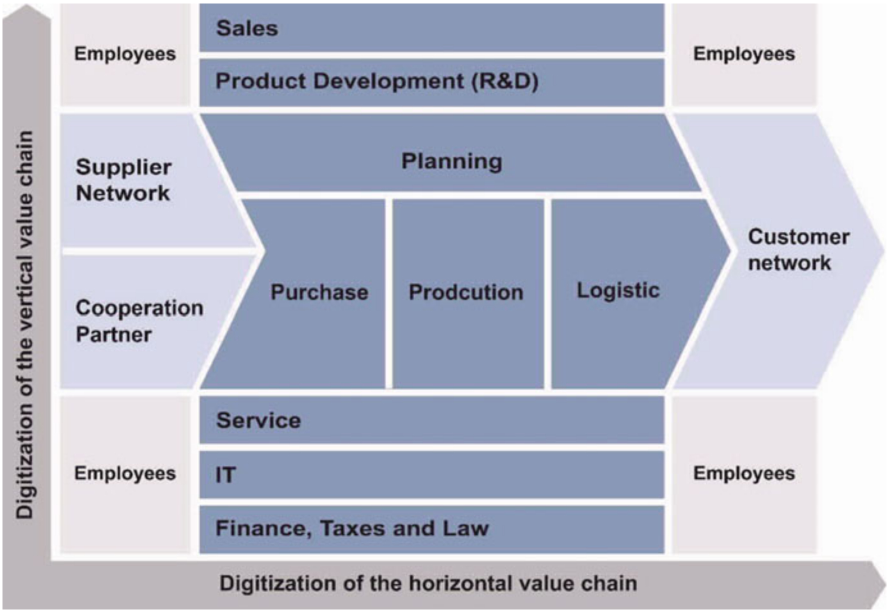

Fig. 6 Horizontal and vertical digitisation of value chains

observer, and actor. As a result, the processed product tells the machine how it wants to be treated. The product does not only know how it will be manufactured; it also stores its entire history in a digital product memory, from the first draft to recycling. The machines, robots, conveyor, and storage systems required for production negotiate amongst themselves and across companies in order to identify free capacities. The entire process can be dynamically designed between the participating partners in various dimensions (quality, time, price, etc.). This in turn leads to a high degree of flexibility for individual production sites which requires standardised processes that enable trust and security for all parties involved. Such real-time optimised value creation results in completely new demands on IT infrastructures of digital economies. While the best networks today have latency times of 10–15 milliseconds, the upcoming 5G standard offers almost real-time capability for data exchange. 5G is fast, instantaneous, reliable, and a prerequisite for a pervasive digitisation of value creation (Kagermann and Winter 2018; Koch et al. 2014).

Vertical: Vertical digitisation ensures a continuous flow of information and data from sales to product development to production and logistics. Optimal networking can prevent system breaks and improve analytical capabilities. In this way, companies can increase quality and flexibility and reduce costs. A digital factory organises itself and can produce effectively under volatile conditions. If, for example, ad hoc orders occur, rescheduling is carried out automatically. Maintenance management is also self-organised. Other unplanned events – such as machine failure, quality fluctuations, or changes to product specifications – are handled automatically. The condition and wear of materials are continuously monitored and forecasted. This digital adaptation of the entire production process prevents unplanned machine downtimes. In addition, administrative inventory management and accounting processes are eliminated, as production resources are self-organising. To a certain extent, digital value creation monitors itself through intelligent sensors and continuous data (Kagermann et al. 2013; Koch et al. 2014).

Employment as an example for the digitalisation of society: The digitalisation of the production system will lead to massive changes in the work and working conditions of the employees. This is associated with social and societal changes that need to be shaped. The acceptance of new technologies is a critical success factor for a successful transformation process. However, acceptance cannot be assumed at all, considering the publicly discussed and predicted changes such as job losses. Companies are therefore urged to involve their employees intensively in the digitalisation process, including qualification and training measures (Abel et al. 2019). Companies affected by digitalisation however will not be deserted by employees, but the role of people and their working conditions are changing more and more. Employees will continue to be urgently needed in the future as active bearers of decisions. They control, regulate, and design intelligently networked production resources and play the decisive role in quality assurance. Employees will also play an important role in the design, installation, retrofitting, and maintenance of intelligent production systems (Kagermann et al. 2013). New digital technologies are also changing the working practices of workers at the shop floor level. For example, machines become adaptive and adapt to people's individual skills and needs and support them in carrying out activities. One example is collaborating robots in industrial manufacturing. In addition to the physical manipulation of the environment by robots, the computer-aided expansion of the perception of reality is gaining importance. In logistics, for example, the use of augmented reality data glasses can support an employee in picking activities. The data goggles enrich the employee's environment with information about the article, its storage location, or transport routes. In addition, virtual reality can be used to optimise the development process for new products, and digitalisation provides developers with a visualisation aid for their work. Digitalisation therefore not only has a profound influence on production machines, but also on the way people work.

Digitisation of Business Models

Digitisation does not only affect the products and value creation of a company but also its business models. Figure 7 shows how the disrupting force of digitisation has entered the most valuable companies worldwide. It is particularly noticeable that the

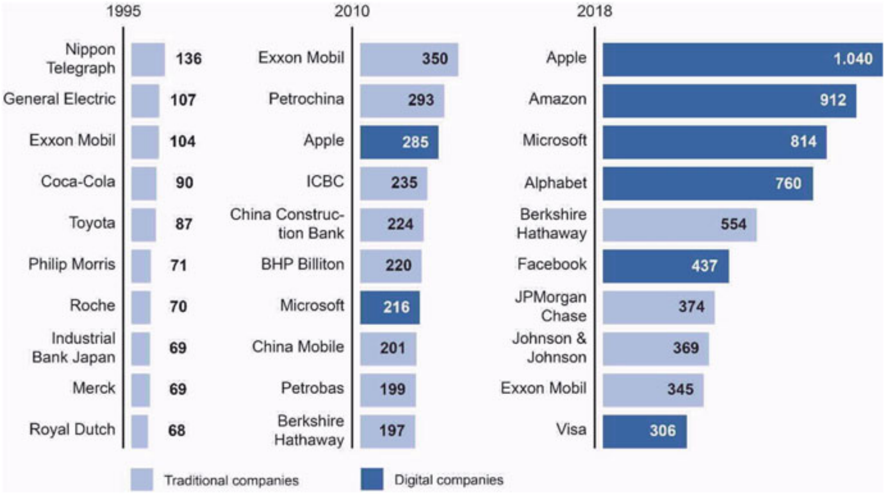

Fig. 7 The ten most valuable companies worldwide in the period 1995 to 2018 by market capitalisation in billion US dollars in the style of Drewel et al. (2018)

number of “digital companies” has increased rapidly in recent times and that their value is threatening to increasingly outstrip that of traditional companies.

As described in the previous sections, a growing proportion of the manufactured products is now smart and supplemented by the collection, storage, analysis, and evaluation of data. These products change the business logic of entire industries and markets by being carriers of digital platforms, enabling smart services and creating digital ecosystems. These new market concepts are closely interlinked and build in parts on each other. Digital platforms in combination with digitised products are the prerequisite for smart services. Smart services, digital platforms, and digitised products form the basis for digital ecosystems. On this foundation, completely new business models can be created. The starting point of these new business models is the orientation towards the customer with his individual needs. Instead of selling a physical product, digital companies aim to offer customers an adequate range of product-service-systems at any time and any place. Figure 8 shows the key aspects of such resulting business models in the age of digitisation. Companies have to exploit the innovation potentials of these aspects in order to secure future business success and stay competitive.

In the following, the three market concepts (1) digital platforms, (2) smart services, and (3) digital ecosystems and the resulting business models as well as the associated changes in society are explained.

Digital platforms: The business logic of industrial production typically follows the linear model of the value chain according to Porter (2014, p. 61ff.). Companies process input goods (raw materials, semi-finished products) in several stages into higher-value end products and sell these to consumers. They generate added value by controlling a sequence of activities that build on each other. Markets that function

Ranked Key Aspects		Important	Medium	Unimportant
1	Strength Networking with customers/partners	72%	24%	4%
2	Offer solutions/systems instead of products	66%	20%	14%
3	Expansion of digital services with additional customer benefits	64%	24%	12%
4	Efficient and Secure Cloud Technologies	44%	31%	25%
5	Establishment/expansion of value-added services (e.g. apps)	46%	29%	25%
6	More direct business with end customers	45%	31%	24%
7	Strengthening of own position in relation to new digital players	39%	31%	30%

Fig. 8 Key aspects of successful business models in the age of digitisation (Koch et al. 2014)

according to this principle are also referred to as one-sided markets or pipeline markets. The classic business logic in many industries is being broken up by digital platforms. A digital platform is a marketplace that connects suppliers and consumers as well as any other players via the Internet and enables value-adding interactions between them (Parker et al. 2016). Markets organised through digital platforms are also referred to as platform markets. According to Rochet and Tirole, platform markets are bilateral or multilateral markets characterised by the so-called indirect network effect (Rochet and Tirole 2006, p. 645). This means that the more participants of a certain group are on the platform, the more attractive a platform is for another group of market participants. Platform markets therefore only function when a certain number of players from all groups are present on the platform. Once this critical mass is reached, however, it forms a highly networked value-added system that significantly increases the opportunities for market transactions and significantly reduces transaction costs. If a company succeeds in positioning itself successfully as a platform provider and in operating a platform business model, it can achieve a dominant market position by acting as an intermediary between the producers and consumers of the market. For a pipeline company, this represents a serious risk as it may lose the direct interface to its customers (Parker et al. 2016).

Platforms have been around for a long time. For example, shopping centres or newspapers are platforms. However, digital platforms require significantly less physical infrastructure and assets and are therefore cheaper and easier to set up. In addition, they enable stronger network effects and better scaling due to easier access for subscribers. In recent years, American and Chinese companies such as Amazon and Alibaba, Google and Baidu, as well as Facebook and Tencent, whose business models are based on digital platforms, have experienced enormous success in the B2C sector and changed the way the members of our society buy products, communicate with each other, or rent a room for a short period. Such platforms are now also developing in the business-to-business (B2B) sector. The winner takes it all principle does not necessarily apply here because complexity and domain knowledge play a greater role. In addition to the advantages mentioned above, platform markets also have structural weaknesses, such as concentration tendencies and the formation of monopolies through economies of scale and network effects, a topic that causes problems for the social network Facebook. Competition law also faces new challenges. If data power tends to consolidate existing market power, it must be clarified when the "abuse" of data power needs to be regulated. Some platforms have the potential to attack established business models such as online passenger transportation services (Kagermann and Winter 2018). The rise of the platform economy shows that companies need to develop products and services for digital platforms in order to participate in the future business of digital platforms (Drewel et al. 2018).

Smart services: Manufacturing companies have been offering services in addition to their products for many years. So far, the focus has mainly been on product-accompanying services, which primarily serve to promote the sale of the products. Exemplary services are financing, conversion and modernisation (design services), maintenance, spare parts management and training (support services), or engineering services for the customer's product development (consulting services) (Spath and Demuß 2006). For some time now, new forms of services have been discussed under the term *smart services* (Allmendinger and Lombreglia 2005). Smart services are digital services that generate added value by evaluating data from networked, intelligent technical systems and are provided via digital platforms. Smart services are thus based on cyber-physical systems or smart products and form an integrated product-service-system. According to Bullinger et al., both the technical system and the service provider are involved in the provision of smart services, whereby the proportion of service provision varies depending on the service and can also be completely omitted (Bullinger et al. 2017). In the latter case (so-called self-services), the main distinguishing feature of a product is that the smart service is offered and monetised as an independent market service. In connection with smart services, data-based business models or smart service business models are therefore also referred to. Examples of smart services are predictive maintenance of machines and systems based on condition and production data (predictive maintenance) or automatic ordering of consumables and resources based on inventory and planned order data.

One example of data-based product-service-systems that can be flexibly adapted to individual customer requirements is car-sharing services. The "use" of the product (e.g., the car) is becoming increasingly important for customers, while "possession" is losing importance. By offering smart services, customers get additional functionality in addition to the physical products. These recommendations are manifold and can result, for example, in an increase in efficiency, reduced costs, preventive maintenance, an increase in reliability, and other possibilities up to a completely new experience. The services are highly customisable and can be adapted to customer needs in real time. Smart services allow a wide range of flexible pricing options as part of the business model. This can, for example, be based on the generated output (number of units), the useful life (time), or performance-based (in the form of profit sharing). Freemium or flat rate strategies are also conceivable. In addition, indirect payment models in which services are provided in exchange for data are already being implemented. Current market conditions as well as availability, supply, and demand in real time can be taken into account in pricing. In addition, there may be other exchange models based on fungible values that include the trading of production capacities, access to mobility, or participation in knowledge building (Kagermann et al. 2018). Companies must develop strategies for smart services in order to profit from the potential of this new concept (Koldewey et al. 2019).

Digital ecosystems: The business activities of manufacturing companies traditionally focus on products and, where appropriate, product-related services. Usually, however, the offer does not only include a single market service, but a comprehensive range of services. Although the various market services complement each other completely, so far they have mainly been isolated services. In the context of digitisation, the services of manufacturing companies are increasingly turning into digital ecosystems. From a supply perspective, a digital ecosystem is a complete system of intelligent products (smart products) and digital services based on them (smart services) networked via digital platforms. According to Ammon and Brem, a digital ecosystem comprises hardware, software, services, and content (Ammon and Brem 2013). In this way it forms a kind of full product range and creates an extremely high benefit for the customer, which clearly exceeds the sum of the utility values of the individual services (Lemke and Brenner 2015). A much quoted example of a digital ecosystem is Apple's range of services. It includes smartphones (hardware), apps (software), telephony, and web access (services) as well as music and books (content). All services are networked via the iOS platform. From a value-added perspective, a digital ecosystem is a network of market participants who interact with each other in service relationships and exchange goods, information, services, and money via digital platforms (Ammon and Brem 2013). The evolutionary stages from an isolated single product to a networked ecosystem are shown in Fig. 3. First, the intelligent products are networked to form product systems. In this way, for example, a tractor becomes part of an integrated agricultural machinery system consisting of combine harvesters, ploughs, and planting machines. By linking different product systems and integrating smart services, a digital ecosystem is created. In agriculture, for example, this is an agricultural management system consisting of an agricultural machinery, irrigation, weather data, and seed optimisation system (Porter and Heppelmann 2014). Companies that are able to build and orchestrate a digital ecosystem or implement an ecosystem business model can dominate a market. As a result of the very broad and coordinated range of services, a strong technological dependence on the user side is usually achieved. This leads to a high level of customer loyalty, since switching to a different, comparable ecosystem is associated with high costs (lock-in effect) (Lemke and Brenner 2015).

Through coevolution and collaboration, companies can jointly offer complementary solutions to their customers and increase their competitiveness. When several innovators successfully collaborate in the same platform environment, innovation ecosystems are created. Global competition will change with the emergence of digital business models and platforms: It will be conducted primarily between digital innovation ecosystems – not just between individual companies. This creates opportunities for start-ups and SMEs to bring their highly specialised competencies to these ecosystems without having to take a greater entrepreneurial risk by building their own platforms. At the same time, data-driven business models, platform markets, and digital ecosystems can have a disruptive effect. Within a very short time, business models that have been successful so far can be cannibalised by third parties – in all industries and all parts of societies. This new perspective on the economy is unusual for many "traditional" industries. Established business models and previously successful companies are being challenged by start-ups, but also by companies outside the industry – above all by large Internet groups. In addition to these radically changed market conditions, the boundaries between manufacturing, services, IT, and Internet industries are blurring. Companies need new competencies, for example, in the areas of IT security and data analysis supported by artificial intelligence. Many companies have already connected their "smart products" to the Internet; they also collect and evaluate corresponding data. On the other hand, the speed with which business models have to change are still underestimated. The members of our society need to adapt to the changes induced by digital ecosystems. They need to develop new competencies, need to understand the chances and risks of digital ecosystems, and need to be open minded towards new services (Kagermann and Winter 2018).

Mobility as an example for the digitalisation of society: The success of innovative business models will have far-reaching social changes, and there is a need for regulation to be expected. Our way of mobility is changing due to new services and the next stages of vehicle automation. Besides improving driving (with new assistance systems), accompanying locomotion with other services will become important. These include entertainment services (especially for automated driving), parking optimisation, and traffic management. Public transport will also change. With the help of sharing models, autonomous vehicles can be used for transport purposes at any time when their owners are not using them themselves. Based on platforms, services will be offered across the entire transport chain in an intermodal transport system. These integrate, for instance, the operation or provision of public transport vehicles with car-sharing services and other travel agents as well as the provision of app-based services for traffic information (Lemmer 2016). Digitalisation in the field of mobility thus opens up completely new possibilities for efficiency, making it possible to reduce chronic congestion, traffic noise, air pollution, and the heavy use of public space by motor vehicles. It is therefore not just a matter of organising mobility, but rather of designing living spaces. This development also depends on the political design of the project. Although most legal systems partly regulate the use of vehicles with automated driving functions, there is a need for further legal adaptations, which will be continued step by step with the development of digital vehicle systems. In addition, there is a need for a legal framework and a policy framework for the development, testing, and deployment of these systems (Lemmer 2016). The success of these systems will depend on their basic acceptance in terms of their social impact.

Societal Challenges and Opportunities of Digitalisation

Whether the search for a suitable means of transport, contactless payment in the supermarket, or communication with family and friends – the boundaries between the real and virtual worlds are merging, and a society is evolving in which digital transformation is penetrating all areas of work and life. Digitalisation has an impact on society through the three levers *value creation*, *products, and services* as well as *business models*. The resulting change creates challenges and opportunities that affect law, ethics, security, work, and ecology (Fig. 9).

Law: The transition to a digital society is accompanied by the challenge of adapting existing law to the changes. These include the adaptation of antitrust law and issues of data protection, liability, labour and consumer law, and intellectual property. With a view to global networking, these issues can only be resolved by embedding them in an international context. The legal framework for autonomous systems is controversially discussed in this debate. These act independently, so that actions of an intelligent system may not be attributable to a human action. In the case of autonomous vehicles, the question arises who must account for decisions made by the autonomous vehicle and who must bear possible legal consequences. For example, the German liability system now ultimately assigns the risk of an accident in road traffic to the vehicle owner. In addition, manufacturers are involved via statutory product liability. However, fully automated and driverless vehicles are subject to further influencing factors. Therefore, in addition to vehicle owners and

Fig. 9 Societal challenges and opportunities of digitalisation

manufacturers, the manufacturers and operators of the vehicle's support technologies must also be included in the system of liability sharing (Bundesministerium für Verkehr und digitale Infrastruktur 2017). When data becomes a critical resource for success, the question of ownership and usage rights also comes into focus. For digital platforms, access to and use of personal customer data is often critical to success. Against this background, society needs technologies that guarantee adequate data sovereignty and allow everyone to determine which data can be shared with whom and which data is worth protecting. Approaches include blockchain technology and industrial data space – a secure data room in which companies can retain control over their data while still managing, linking, and exchanging it securely (Kagermann and Winter 2018).

Ethics: The example of autonomous vehicles also shows that autonomous systems take decisions with ethical dimensions. Autonomous systems are not able to judge their decisions according to moral standards. The ethical requirements are therefore much more focused on the process of programming, which should follow a value-based design. Accordingly, the integrity of life and limb or the principle of gender equality must be mapped in the knowledge bases of intelligent systems. For example, artificial intelligence is not allowed to discriminate based on ethnicity when granting loans.

Security: IT security and data protection are another social challenge induced by digital technologies. The Internet is the system-critical infrastructure in a digitised society and is its backbone. With increasing digitisation, the danger of hacker attacks also increases (e.g., through hackers). In a networked society, the effects of an attack are quickly devastating, so that individuals, entire companies, or government institutions can suffer serious damage. One example is the attack on the German government network published in 2018. The attackers were able to penetrate the German government network, which was separated from the public network, and were interested in sensitive data from ministries.

Work: Digitalisation is accompanied by a fundamental change in the world of work and can lead to a more humane work-environment and more self-responsible. At the same time, there is pressure for rationalisation and new competence requirements for workforces. These challenges must be addressed by companies at an early stage, for which a fundamental adjustment is necessary (Jürgens et al. 2017). Critical fields of action are a flexible and creativity-enhancing work organisation and continuous training of employees. Digitalisation offers new opportunities for flexible and agile working. In this context, employees are given the opportunity to make more independent decisions or to work from home and companies benefit, because they can respond better to rapidly changing circumstances and customer requirements. Furthermore, new feedback tools can strengthen performance management and therefore improve the feedback between management and employees and the quality of (agile) work. These changing working conditions due to digitalisation require employees to continually update and develop their skills. Therefore, lifelong learning is the key to increased productivity and innovation in a digitalised society. Empowering employees to acquire knowledge and skills on an ongoing basis ensures their employability. In addition, hybrid competences will be in high demand in the future instead of further specialisations (e.g., engineers with software/data competence) (Jacobs et al. 2018).

Ecology: The far-reaching negative consequences of the existing production system for the environment and health are evident. The pollution of the oceans and the export of garbage are increasingly coming to the attention of the public. In addition to ethical considerations, it can also make sense from an entrepreneurial and economic point of view to redesign the way resources are used. The concept of circular economy (CE), which aims at a nature-compatible design of economic systems, corresponds to this. CE aims to minimise negative environmental impacts by closing and slowing down material cycles. In this sense, the implementation of CE practices should decouple the rate of economic growth from environmental impacts. In various approaches of CE, decisive innovations are taking place on the basis of digitalisation. It enables, for example, the continuous recording of material and resource flows in production all through to recycling. This results in potentials for process optimisation, higher material efficiency, and thus lower consumption of material and energy. In addition, products can be shared through digital platforms, resulting in significantly better capacity utilisation. Following this principle, digital sharing platforms, for example, can contribute to greater efficiency and sustainability along the entire product life cycle by making better use of cars, machines, or homes (Weber and Stuchtey 2019).

So, digitalisation affects the way we live, work, and learn. Well-known concerns are that people become transparent, skills obsolete, and jobs rationalised. In addition, there is the fear of loss of control and insecurity: Will the digitalisation of value creation really exploit the potential for the working population in terms of greater self-determination, better working conditions, and more individual employment qualifications? Will there be enough new job profiles to replace those that will be lost in the digital transformation of our society? Will there be a polarisation in the labour market, as the low-skilled are more affected than the high-skilled? One thing is certain: We are at a tipping point. The outlook is correspondingly ambivalent. Artificial intelligence could also be used to automate occupations with a higher level of qualification. Estimates for the legal sector assume that 30–50% of the tasks currently performed by young lawyers can be automated (Kagermann and Winter 2018). At the same time, completely new activities are emerging thanks to technological developments. Estimates for electricity and logistics industries indicate that digitalisation could create up to six million jobs worldwide between 2016 and 2025 (World Economic Forum 2016). Besides, the further rationalisation and automation also offers an opportunity to absorb the negative effects of demographic change.

Outlook

Digitisation affects not only future products and services but also the way they are developed. Work will become detached from local boundaries and rigid organisational structures in virtual and globally networked spaces. Correspondingly, companies must react by adapting organisational structures, processes, methods, and tools and in particular the form of cooperation. Innovation successes will only be achieved in the long run if it is possible to professionally develop complex technical systems on a large scale (Gausemeier et al. 2019). The individual activities of product development are increasingly networked and are supported more than ever by IT-Tools. Processes, methods, organisational structures, and especially the form of cooperation are changing accordingly. New challenges arise for the development of intelligent systems. No discipline can claim to develop such a system alone because of the complexity of a technical system. More than ever, the individual activities in system development are supported by digital solutions and IT-Tools. Systems engineering has the potential to integrate disciplines and diverse aspects and to form a sound basis for a mandatory holistic product development methodology in the age of digitisation. Systems engineering claims to effectively support the orchestration of the actors in the development of complex systems. Systems engineering focuses on the development of holistic solutions to complex problems (Hitchins 2007) and sees itself as an integrated and interdisciplinary school for the development of engineering systems. All relevant design aspects, such as resilience, security, sustainability, usability, manufacturability, and business model, but also aspects such as requirements, functionality, behaviour, and design are taken into account. It makes a significant contribution to the secure and rapid development of multidisciplinary systems and thus claims to support the orchestration of actors in the development of complex engineering systems. This is also a basic requirement for mastering the social challenges in the fields of economy, law, ethics, security, work, and ecology, but also for seizing the opportunities in these areas.

In times of digital transformation, companies need completely new competencies, for example, in the areas of data linking and analysis using artificial intelligence and machine learning. They are increasingly looking for these in science and applied research. This gives a new urgency to the design and optimisation of knowledge, technology, and knowledge transfer. However, the established forms of knowledge transfer between science and industry also face major challenges. Start-ups in particular are slowing down the supply gap for follow-up and growth financing. One example is the shortening of innovation cycles. Time to market is often more important than perfecting a product or the emergence of platform companies and digital ecosystems. It changes proven cooperation and relationships. Companies and science have to open up to new cooperation partners and overcome cultural boundaries in the process. The transfer in the science system should be firmly anchored as a third mission alongside research and teaching. We need even closer networking between science and industry to shape the complex tasks of the future.

Against this background, there are seven levers for increasing the innovative capability: (1) creativity, which starts with the end user; (2) agility, which promotes flexible, proactive action; (3) data and model-centred work in the sense of Model Based Systems Engineering (MBSE); (4) virtualisation, i.e., the consistent creation and analysis of digital models with the aim of creating the so-called "model-based" system and "digital twin" as a counterpart to the real operating system; (5) digital consistency in product development and the further phases of the product life cycle; (6) assistance systems, which take over routine tasks in market performance development and ensure the consistency of development information; and (7) communication and cooperation of experts in market performance development as well as on the meta level with stakeholders.

Cross-References

► Data-Driven Preference Modelling in Engineering Systems Design
► Sustainable Futures from an Engineering Systems Perspective
► Systems Thinking: Practical Insights on Systems-Led Design in Socio-Technical Engineering Systems
► Technical and Social Complexity
► Transitioning to Sustainable Engineering Systems

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Systems Thinking: Practical Insights on Systems-Led Design in Socio-Technical Engineering Systems

7

Misha Kaur and Luke Craven

Contents

Abstract

Complex socio-technical engineering systems shape the world around us. Examples include the generation and distribution of energy, global communication, healthcare delivery, and global supply chains. Understanding and engaging with complexity in each of these examples requires new frameworks, tools, and mindsets. Systems thinking and systems-led design can be operationalised and applied to the context of designing or intervening in socio-technical systems. In this chapter, we explore the history and emergence of

M. Kaur (✉) · L. Craven
School of Business, UNSW, Canberra, Australia
e-mail: Misha.kaur@student.unsw.edu.au; l.craven@unsw.edu.au

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systems thinking and systems-led design practice to-date, their overlap and resonance, and how they have been applied to the challenge of tax system design at the Australian Taxation Office. We conclude by including lessons learnt and opportunities of the future in using systems-led design.

Keywords

Design · Complexity · Engineering systems design · Engineering systems · Public sector · Systems-led design · Systems thinking

Introduction

The world around us is irreducibly complex. In theory and practice, there is increasing recognition that we lack the concepts, approaches, or tools to adequately explain or engage with that complexity. Systems thinking has gained momentum helping to understand and respond to complex phenomena. While there is significant enthusiasm around the concept of systems thinking, it has largely been discussed as a theoretical construct and has struggled to cement itself into practice. Systems thinking can be difficult to operationalise and apply to the context of designing or intervening in socio-technical systems. This chapter will discuss what it means for the world to be complex, specifically the complexity of socio-technical engineering systems characterised by high social and technical complexity, intricacy of human behaviour and uncertainty of long life-cycles (De Weck et al. 2011), and the emergence of systems thinking as a response to that complexity. It introduces a practical orientation of systems thinking that we call systems-led design. Systems-led design embeds systems thinking into design practice to create a mindset and approach to help us understand, design, and intervene in socio-technical engineering systems more effectively. This chapter will complement theoretical foundations with practical examples and insights from our experience in developing, implementing, and embedding this practice in an Australian public sector context.

Socio-Technical Engineering Systems and Complexity

Despite the widespread use of the term system, multiple definitions co-exist, reflecting the multidimensional nature of the concept (Hieronymi 2013). In General Systems Theory (Bertalanffy 1968) systems consist of parts and their interactions that together produce properties not obtainable by the elements alone. This can refer to a wide range of systems across multiple disciplines: sociologists have typically emphasised social systems, psychologists cognitive systems, computer scientists information systems, and engineers hardware systems. (For an overview, see also Sillito et al. In General Systems Theory, no discipline has a monopoly on science – all are valid.) The term socio-technical system was originally coined by Emery and Trist to describe systems that involve interactions between humans, machines, and the environmental aspects of the system (Baxter and Sommerville 2011). Today, these interactions are trust of most systems and require all factors, including people, machines, and the broader context to be considered when developing, intervening, or engaging with such systems.

Such systems can be seen as complex systems (De Weck et al. 2011). There is considerable variation in the way that complexity is described, used, and understood and we cannot claim to speak here to all complexity theories (we here refer also to other chapters in this Handbook specifically focusing on social and technical complexity and on emergence and dynamics). Instead we take our lead from the so-called British School of complexity that seeks to apply the complexity sciences to social scientific research and stems largely from the work of David Byrne (2002) and Paul Cilliers (1998). Taking Bryne and Cilliers as our starting point, we consider key ideas from complexity theory to be interdependence, non-linearity, emergent features, adaptive agents, and open systems. It is crucial to note, however, that while these characteristics help with talking about complexity in an abstract way, we also need to develop methods to measure and understand how complexity manifests in everyday life. This is where we see a role for design and systems practices that ground this thinking in application to everyday problems.

First, a complex system cannot be explained merely by breaking it down into its component parts because those parts are interdependent: elements interact with each other, share information, and combine to produce systemic behaviour (Byrne 2002; Cilliers 1998).

Second, the behaviour of complex systems exhibits non-linear dynamics produced by feedback loops in which some forms of energy or action are dampened (negative feedback) while others are amplified (positive feedback) (Cilliers 1998; Sterman 2001). Feedback is a core part of interdependence and makes the outcome of systemic dynamics difficult to predict. As Jervis (1997, p. 125) notes, "feedbacks are central to the way [complex] systems behave. A change in an element or relationship often alters others, which in turn affect the original one". In complex systems, as Byrne (2002) suggests, feedback is about the consequences of non-linear, random change over time. While in simpler systems, feedback may be linear, predictable and consistent, non-linearity guarantees that seemingly minor actions can have large effects and large actions can have small effects. It is a precondition for complexity. Perrow's (2011) work illustrates dramatically the implications of interdependence and non-linearity by distinguishing between accidents that occur in tightly coupled systems and in loosely coupled systems. In tightly coupled systems relatively trivial changes in one element or dimension can spread rapidly and unpredictably through the system and have dramatic and unpredictable effects.

Third, complex systems exhibit emergence or behaviour that evolves from the interaction between elements in which, as the colloquialism goes, the whole is greater than the sum of its parts. Put another way, in a nonlinear system adding two base elements to one another can induce dramatic new effects reflecting the onset of cooperativity between the constituent elements. This can give rise to unexpected structures and events whose properties can be quite different from those base elements (Nicolis 1995, pp. 1–2). This makes the system difficult to control and, again, focuses our attention on the rules of interaction and the extent to which they are followed. A problematic tendency in the social sciences is to engage with the social world in terms of correlations between variables, which are then evaluated using standard methodological techniques oriented towards the evaluation of the "net effects" of causal variables. That is, as Ragin (2000, p. 15) has put it, "each causal condition [is] conceived as an analytically distinct variable [that] has an independent impact on the outcome". But if we take interconnectedness and non-linearity as a given, these practices lose their practical purchase. Net effects are impossible to isolate.

Fourth, in complex systems the behaviour of adaptive agents has a role in shaping the structure of the system. Adaptation here describes a process within which an agent changes to respond to its environment, seeking to gain equilibrium. Complex systems are in dialectic with the agents that operate within them. As Reed and Harvey (1992, p. 370) argue "far-from-equilibrium conditions can originate in the values and actions of humans themselves". Systemic dynamics, then, emerge from the agency of their actors, their collective goals, their conflicts, and their negotiations, but the existing structure of the system plays a significant role in conditioning the actors. It is this coevolution that produces change in a system (Mitchell 2011; Cilliers 1998). Crucially, though, we must resist the temptation to dissolve agents into their structures or to see structures as the result of agential emergence. Doing so creates, as Donati and Archer (2015) have noted, a theoretical problem of "central conflation" in which agents and structures are fused so that they become analytically inseparable. We must instead seek to view agents and their structures as having distinct qualities that can be treated as objects of knowledge and explanation.

Finally, the boundaries of a given complex system are open (Cilliers 1998, p. 4), as "the system" cannot be easily distinguished from the broader dynamics in which it is situated. For example, while we could analyse Australia as a complex bounded system doing so would exclude elements of the international environment that undoubtedly influence Australian outcomes. The core point here is that where and how we draw or define the boundary of system is a methodological choice rather than something intrinsic or essential to the system itself (Cilliers 2000, pp. 27–8). This has implications for understanding discrete phenomena inside particular systems. Academic engagements always involve boundary judgments and we need to more deeply interrogate the benefits and limitations of particular framing practices.

The concepts outlined here illustrate a range of ideas and perspectives, many of which are closely related to each other. How these concepts and categories are defined is contentious. As Mitchell (2011, p. 95) notes, "there is not yet a single science of complexity but rather several different sciences of complexity with different notions of what complexity means. Some of these notions are formal, and some are still very informal". We should view therefore the idea of complexity as a "sensitising concept" (Blumer 1954) that can provide some initial direction in understanding how to comprehend and respond to socio-technical engineering systems.

Systems Thinking and a Brief History

In socio-technical engineering systems, elements would designate components or subsystems (hardware, software, facilities, parts, process steps), humans and social entities (human level elements such as information flows or work processes, and broader social scale such as social norms, coalitions, organisations, information networks, and power dynamics (e.g. Rouse 2015; de Weck et al. 2011). Connections would be the interfaces between these elements, including technical links, human-technical interfaces, and strictly social relationships, along with their broader environment.

Designing or intervening in such systems is entirely different than designing a purely technical system, due to the complexity of human unpredictability, intellect, and irrationality. Public sector and other individuals have traditionally dealt with social problems through designing and implementing discrete interventions layered on top of each other. However, given the complexity of socio-technical systems, interventions will create adaptations and changes within the system, and may shift consequences from one part of the system to another or address symptoms while ignoring drivers (OECD 2017a).

This has led to growing interest in the use of systems thinking and design. Design, systems engineering, and systems thinking have interlinked philosophical foundations and share, in some cases, methodologies. As such, the next two sections will offer a brief overview and history of systems thinking and design practices.

Systems thinking will be essential to address global issues in an era of rapid and disruptive change (Ramos and Hynes 2019). Systems thinking was a term first coined by Richmond in 1987 and is an umbrella term for a range of fields evolving from general systems science (Costa Junior et al. 2018) and General Systems Theory (GST), which was developed by Von Bertalanffy for conducting inquiry and exploration of whole systems (Von Bertalanffy 1968, 1972). Systems thinking is thought to comprise a mindset and conceptual framework primarily focused on the concept of an adaptive whole, which shifts according to its environment (Checkland and Poulter 2006; John 2012), and exploration of the parts of a system, and their interdependences (Amagoh 2016; Boulding 1956). Richmond (1994) saw systems thinking as a necessary means to deal with the increasing interconnectedness and complexity of the world. Richmond's view on the importance of systems thinking in dealing with contemporary society's complexity has been agreed with by many systems thinking researchers (Meadows 2008; Plate and Monroe 2014; Senge 1990; Sterman 2002).

Despite this widespread agreement on its importance, systems thinking does not have a single definition in the literature (Arnold and Wade 2015). Definitions put forward emphasise different foci, ranging from systems thinking as a set of characteristics (Kopainsky et al. 2011; Stave and Hopper 2007; Sweeney and Sterman 2000; Valerdi and Rouse 2010), systems thinking as comprised of a purpose (Richmond 1994) and what it does (Senge 1990), or systems thinking as a system itself (Arnold and Wade 2015). However, an analysis of seminal and recent literature

Table 1 Core features of systems thinking

Feature	Literature references
Whole systems, and how the parts within the system give rise to the whole	Ackoff (2004), Arnold and Wade (2015, 2017), Cabrera and Cabrera (2015), Richmond (1994), Senge (1990), Stave and Hopper (2007), Valerdi and Rouse (2010)
Definition of the boundary of a system of interest, and the interrelationships of the parts (elements)	Arnold and Wade (2015, 2017), Cabrera and Cabrera (2015), Gharajedaghi (2011), Peter Jones (2014), Kopainsky et al. (2011), Meadows (2008), Senge (1990), Sillitto (2021), Stave and Hopper (2007), Sweeney and Sterman (2000), Valerdi and Rouse (2010)
Consideration of multiple perspectives and the individuals' mental models that give rise to these perspectives	Arnold and Wade (2017), Cabrera and Cabrera (2015), Garrity (2018), Khan (2020), McCabe and Halog (2018), Midgley and Rajagopalan (2019)

reveals consistent features of what systems thinking seeks to focus on as a practice, outlined in Table 1.

Overtime, systems thinking has created and drawn on many approaches, including hard systems, soft systems (Luoma 2007), critical systems thinking approaches (Costa Junior et al. 2018), and those that extend beyond critical systems thinking (Midgley and Rajagopalan 2019) into a plurality of approaches.

Prominent scholars in the field of systems thinking recognise this evolution and development of systems thinking has occurred in "waves" (Amissah et al. 2020), as originated by Flood, Jackson, and Keyes (Flood and Jackson 1991; Jackson and Keys 1984), and built upon by Midgley (Burton 2003; Leleur 2014; Midgley 2000). This metaphor of four waves has been widely used as a conceptual and historical model for systems thinking, and built upon by contemporary researchers (Amissah et al. 2020; Cabrera and Cabrera 2015; Jung and Love 2017; Midgley and Rajagopalan 2019).

First Wave of Systems Thinking and Criticisms

The first wave of systems thinking gained popularity in the 1950s and 1960s with the earliest ideas including theories such as general and open system theories of von Bertalanffy (1968), which began to influence management practices (Kast and Rosenzweig 1972).The first wave of thinking is primarily known to be related to "hard" or technical systems (Amissah et al. 2020). Hard systems approaches originated during research into decision making to support military capability in the Second World War (Checkland 1994). Scholars in the field began considering how inputs, conditions, and feedback loops (where parts of the system might act as an input into another part of the system) affected a system (Jones 2013). Methodologies used within hard systems approaches are often employed in an attempt to predict and control the behaviour of the system. Hard systems approaches initially focused on decisions relating to manufacturing and technology problems, which could be controlled and manipulated to achieve pre-determined outcomes (Checkland 1994). The concept and adoption of modelling and controlling inputs and outputs has since expanded to understanding human behaviour within management science (Kast and Rosenzweig 1972; Malcolm 2017). Da Costa Junior et al. (2019) stipulate that problem-solving processes within hard systems thinking are the closest to that traditionally used in design. More specifically, that solutions are deliberated on, preferred solutions are selected, and final solutions are further developed and implemented (Bausch 2014).

Criticisms: However, during the late 1960s and then in the 1970s and 1980s, scholars started to put forward criticisms of the underlying assumptions and practical application of the first wave approaches to systems thinking (Midgley and Rajagopalan 2019). First wave approaches were criticised for regarding models of systems as representations of reality, rather than as useful aids to help understanding of certain contexts between people with different perspectives (Checkland 1981; Espejo and Harnden 1989). Midgley and Rajagopalan (2019) summarise that the key issue with this is that if models are regarded as the "truth", then people with other perspectives can be easily dismissed, which can obstruct learning and stimulate conflict. Resultantly, recommendations for change may not consider those who would be affected by, or who would be required for the successful implementation of, that change. The result could be recommendations that were regarded as unacceptable by stakeholders, and were therefore not implemented, or were resisted if implementation were attempted (Rosenhead 1989). The first wave approaches were also criticised for viewing individual human beings as predictable objects that could be controlled as part of larger systems, instead of individuals with their own beliefs, goals, and mental models that may or may not harmonise with the wider environment (Checkland 1981).

Given the known complexity of problems, and the diversity of individuals with differing belief systems involved, that are being dealt with by designers today, it is futile to think that such models can ever be the "truth" or controllable. Hence, in this context, systems thinking has been argued by some authors: as being likened to earlier reductionist approaches that failed to consider subjectivity (Ackoff 1979; Checkland 1981), as only adequate to address well-framed problems (Malcolm 2017), and as possibly leading to the implementation of solutions to the detriment of other opportunities (Bausch 2014).

Second Wave of Systems Thinking and Criticisms

These criticisms led to a new "wave" of thinking that shifted in the paradigm underpinning the practical application of systems thinking (Midgley and Rajagopalan 2019). In this second wave, scholars (e.g., Checkland 1981; Churchman 1979) shifted from proposing that models of systems were the "truth" to noting that they are constructs of elements within a chosen boundary to aid understanding. Identifying the boundaries that guide what is of interest in the system is always subjective and is made up of the perspectives of people, participatory practice became essential (Midgley and Rajagopalan 2019). Therefore, it was important to ensure stakeholders were involved in this process. Thus, this wave of thinking gave rise to adapted methodologies to incorporate stakeholder participation, for example, modelling of system dynamics (e.g., Senge 1990), and new approaches, most notably soft systems thinking (Checkland 1981).

Soft systems thinking became a core concept within the second wave of systems thinking. Soft systems thinking is an approach that recognised that problem situations can be socially complex in nature (Ackoff 1979; Checkland 1978; Oliga 1988) and brought greater recognition of human values and subjectivity within systems (Checkland 1994; Oliga 1988). This assumes that few real-world problems can be clearly defined, and therefore, soft systems thinking was seen to be a more appropriate methodology for dealing with ill-defined, wicked problems (Checkland and Poulter 2006). The approaches used in systems thinking seek to understand the broader environment and individual interpretations of the world to create shared understanding (Jackson 2001) between actors involved. This is done through tools for problem exploration, making models to understand the system or question the situation, and taking action to improve situations (Peter Checkland and Poulter 2006). For example diagrammatic mapping such as giga-mapping (Sevaldson and Ryan 2014), causal loop diagrams (Bureš 2017), or rich picture making provide visualisations to consider relationships within systems. This enables patterns to be analysed and identified, leading to a level of understanding of real-world contexts that is not readily available through reductionist approaches (Stolterman and Nelson 2012). Other methods related to soft systems thinking, such as Meadow's (1999) leverage points within a system, allow practitioners to question the right point and type of intervention in order to produce a desired result.

Criticisms: While the popularity of soft systems thinking and related approaches of the second wave of systems thinking increased in the 1970s and 1980s, so too did criticisms. The primary criticism centred on the theme that the participative nature of its approaches was not able to account for, or be achieved, when situations are dominated by coercive relationships or complex power dynamics (Jackson 2001; Mingers 1980). This is because it assumed that open communication between stakeholders would be unproblematic; however, it is often actually constrained (Jackson 1991). Notwithstanding this, the primary strengths of soft systems methodologies as they relate to design practice lies in their holistic inquiry into whole systems which problems deal with. More specifically, the shift in design practice to more participatory approaches required greater collaboration by actors involved (Nelson 2008). Soft system thinkers such as Churchman, Ackoff, and Checkland advocated for respect for all stakeholders involved in the problem situation (da Costa Junior et al. 2019), similar to that of participatory design approaches. While Checkland and Poulter (2006) do indicate that there are methods that include action, a lack of action is one of the key criticisms of soft systems thinking (Ryan 2016), meaning that inquiry into a system does not always turn into delivery of interventions to deal with the complex problems.

Third Wave of Systems Thinking and Criticisms

The third wave of systems thinking began to take shape towards the end of the 1980s (Midgley and Rajagopalan 2019). This came under the broader category of critical systems thinking, which was built upon Ulrich's (Ulrich 2003) theories of critical systems approaches and heuristics, and Jackson and Key's (1984) arguments for pluralism in methodologies.

Critical systems thinking emerged as a response to the limitations of both hard and soft systems thinking, with the goal to reconstitute systems thinking as an approach to problem handling (Ulrich 2003). It also used techniques such as Critical Systems Heuristics (Ulrich 1983), to prevent adverse influences in communication, which can interfere with achievement of an open debate between actors involved during the understanding, design, and implementation of systems (da Costa Junior et al. 2019). Ulrich (2003) states that critical systems thinking also stemmed from the insight that all approaches have different strengths and weaknesses so it is sensible to use them to address different purposes. Critical systems thinking allows for this as it field adopts pluralism as a central tenet, which allows for the strengths of various trends in systems thinking to be appropriately used (Ulrich 2003). Proponents of this third wave of systems thinking approaches argue that it can provide valuable insights into the purpose for choosing certain methods, tools, or techniques (Murthy 2000). This can be done through increased understanding of strengths and weaknesses of methodologies (Oliga 1988), making explicit the social consequences of methodologies and identifying tools that can promote human emancipation (Jackson 2001; Ulrich 2003). For design practice, this is useful as the consequences of designed actions or solutions can have major implications and therefore is important to choose the right methods for the right context and situation.

Criticisms: However, a noted limitation of methodological pluralism is that systems thinking can be reduced to a set of tools that anyone can perform, once that have the requisite literacy in the broad set of approaches available (Cabrera 2016). The risk with this "tool-based" frame is that those attempting to use systems thinking do not consider the broader contexts which promote their effective use, including changes to personal mindsets and organisational structures, for example. The third wave also created siloes in the way that systems thinking was practised, as people were not able to practically to achieve this literacy in different areas across the discipline, which often operated on different assumptions and sought different outcomes. This tribalism made it difficult for those looking to innovate and develop systems thinking approaches through integration or mixed-methods use.

Emerging Fourth Wave of Systems Thinking

An emerging fourth wave of systems thinking attempts to unify and advance the field of systems thinking by recognising the cognitive aspects of individuals considered within the system, and that systems are primarily complex systems (Cabrera 2016). The first three waves of systems thinking encouraged deeper thinking and

Table 2 Mapping of systems thinking core features to Cabrera's (2016) key skills

Feature	Concept
Whole systems, and how the parts within the system give rise to the whole	Exploring how elements combine to make a system
Definition of the boundary of a system of interest, and the interrelationships of the parts (elements)	Making boundary distinctions Understanding relationships between elements
Consideration of multiple perspectives and the individuals' mental models that give rise to these perspectives	Appreciating the implications of multiple perspectives

understanding of systems and how people within them think, while the fourth wave seeks to understand why people think the way they do, and why patterns within the system give rise to certain events or behaviours (Amissah et al. 2020). By doing so, it may also allow designers to identify levers that intervene on the influences of why they think that way, rather than what people ask for or say, thus potentially providing a greater range of, and potentially deeper set of, levers in order to change a system.

In analysing the historical evolution of systems thinking, and building on the fourth wave, Cabrera (2016) offered the following four universal concepts of what systems thinking involves: people make distinctions (boundary judgements differentiating phenomena of interest from other things) of systems (wholes made up of parts), where the parts are in relationship with one another (and systems are also related to other systems), and every distinction, system, and relationship is viewed from a perspective (Midgley and Rajagopalan 2019). More importantly, Cabrera (2016) has argued that each of these four concepts is a skill, and therefore there are four skills required to undertake systems thinking effectively: making boundary distinctions, exploring how elements combine to make a system, understanding relationships between elements, and appreciating the implications of multiple perspectives (Midgley and Rajagopalan 2019). These four concepts can be readily mapped to the core features of systems thinking identified above (Table 2).

Systems Thinking Dealing with Socio-technical System Challenges

Systems thinking is now known as the practical application of systems ideas to address complex environmental, social, and organisational problems (Midgley and Rajagopalan 2019). As a practice to deal with complex challenges, systems thinking has been argued to replace reductionism (the belief that things can be reduced to their individual parts) with expansionism or holism (the system might be a sub-component of some larger system) and indeterminism (John 2012). Reductionist approaches have been argued to not be able to depict or understand complex and dynamic scenarios (Dominici 2012). Therefore, systems thinking is a valuable corrective to reductionism to understand social phenomena (Gharajedaghi 2011; Jackson 2001). However, it has been pointed out that this claim is not wholly justified because an inquiry that analyses the parts still considers their interdependency to the whole through some principles (Murthy 2000). Murthy's argument can perhaps be negated as long as systems thinking acknowledges that an inquiry into the parts is to create an understanding of the whole rather than to fix each part separately.

The adoption of systems thinking has been argued to be helpful in illustrating the complexity inherent to socio-technical engineering systems, dealing with wicked or complex societal problems (da Costa Junior et al. 2019). Mechanisms put forward to do this include better problem exploration processes and visualisations (DeTombe 2015; Sevaldson 2013), acknowledging and considering the plurality of actors involved including their individual goals and beliefs, analysing complex whole systems as opposed to breaking them down (Nelson 2008), and embracing multiple perspectives and creating awareness of the differences in social relationships (Daellenbach 2001; Zheng and Stahl 2011). Key to this is also looking more deeply at the patterns of behaviour and relationships of the systems' parts that may be responsible for the observable events (Adam 2014, p. 3). These less observable patterns include mental models, assumptions, and beliefs that individuals use to guide their actions, decisions, and behaviours (Meadows 2008). However, it is worthwhile recognising that systems thinking has been criticised for its lack of action, as well as its ambiguous language (Sevaldson 2018), and lack of adoption or integration with public practice and decision makers (Ackoff 2004).

There are some examples where systems thinking has explicitly been applied to socio-technical engineering systems. For example, Seddon's Vanguard Method (Seddon 2003; O'Donovan 2014) has been developed for the use of delivering services. It focused not only on the requirements of the user but considers also checking systemic conditions and capabilities in order to eliminate waste and on system processes or elements that will generate more value for services users. As such it offers learning processes that are necessary to change institutional processes along with the technical and human interactions. This method has been applied in the Netherland's in reforming the child protection system. Other examples of systems approaches being used to deal with socio-technical systems include health prevention and public health strategies, environmental strategies and waste oil management, sustainable food consumption in Norway, and infrastructure planning in Australia (Pepper et al. 2016). The successes of systems approaches have not been researched widely; however, the Munro Review of Child Protection offers some insights into this. The Munro Review of Child Protection in England in 2010 (Munro 2010) demonstrated the effects of individual or layered reforms on the objectives of the system and the broader challenges with intervening or taking effective action within socio-technical systems.

Despite the enthusiasm and long history around systems thinking, it has largely been discussed as theoretical construct and there are limited examples of its application in practice. Systems thinking can be difficult to operationalise by public sectors and others in the context of designing or intervening in socio-technical engineering systems for several reasons.

At an individual level, there is some way to go in building the knowledge, skills, and capabilities for people to engage with the complexity of systems and therefore use systems thinking to deal with challenges. Individuals need to build muscle in sitting with discomfort and ambiguity and unlearning certain linear or simplistic mental models that prevent a systemic way of thinking.

In the public sector where policymakers are dealing with social technical system challenges every day, further contextual issues arise. Firstly, as challenges become increasingly complex, the amount of evidence requires to fully diagnose a challenge or problem may be too resource intensive and in earnest, impossible and perhaps not useful for complex systems as there are often no definitive answers in said challenges. The recent emphasis on evidence-based policymaking appears to assume that the public sector is able to wait until a sufficient amount of data before acting (Head 2010), therefore driving a narrower focus on parts where evidence can be sought rather than looking at complex socio-technical challenges in a holistic way. Secondly, feedback is a core principle of systems thinking, utilising feedback loops to provide information on the behaviours of systems and further interventions to a system. They are a mechanism that offers meaningful insights that can be applied to socio-technical systems. However, this requires open-ended processes (OECD 2017a) that imply a receptiveness to alternate ways of doing things, differing opinions, and a tolerance for risks. Unfortunately, measurement systems, procurement, and political cycles often do not align with open ended processes. Thirdly, when dealing with socio-technical systems, new interventions of systems models can be designed in abstract but in reality needs to be built within existing systems and constraints. This is because socio-technical engineering systems such as healthcare, education, and infrastructure cannot be easily turned off, redesigned, and restarted. Therefore, systems thinkers and those responsible for designing or improving socio-technical systems should ask themselves critical questions about how to reform the elements within the system without requiring shutting off of essential services (OECD 2017a).

The widespread discussion of systems approaches and also the challenges associated with using underlying systems thinking features from Table 1 has seen the proliferation of innovative practices and capabilities globally aimed towards dealing with complex systems and issues. Notable efforts include Helsinki's Design Lab SITRA who have deployed systems thinking into their design of issues such as decarbonisation (OECD 2017b), The Australian Centre for Social Innovation applies systems-based design approaches to deal with socio-technical issues such as in working with dysfunctional families by looking for ways to intervene in the system at crisis points, the MaRS Solutions Lab that uses design and systems thinking to deal with societal issues, and the Danish Design Centre that also draws on design and systems approaches (Bason 2017). Most of these are grounded in design practices.

Systems Thinking and Design Practice: Complementary Approaches

There has been a proliferation in the use of design practices for socio-technical engineering systems, including consideration of participatory processes of intervening in such systems. The increased popularity of design in complex challenges has led to the proliferation of different toolboxes and guides on how to use design, some of which mention systems thinking (OECD 2017a). While certain scholars and practitioners view systems thinking as part of a design broader skillset (Mulgan 2014) and others view the opposite (e.g., Gharajedaghi 2011), both practices are not the same and have originated from different places. However, design is a useful foundation for integrating systems thinking into the approaches used for working in or with socio-technical engineering systems.

Design as a practice has been more integrated with intervening in complex systems such as socio-technical systems and is action oriented and therefore presents its own opportunities for systems thinking. Design has been put forward by advocates as an alternative approach to reductionist approaches (which break down something into its constituent parts in order to understand or study it) for problem solving (Baran and Lewandowski 2017; Brown and Wyatt 2010; Graham 2013; Kelley 2001) and dealing with the challenges facing society today (Dorst 2015).

However, researchers and practitioners have put forward criticisms related to the practical ability of design to deal effectively with the increasingly complex socio-technical systems. These criticisms relate to design's inability to understand and deal with complexity, issues stemming from its human centricity including its focus on the human or user at the expense of other users or system elements, and the tendency of design to degenerate into a formulaic process when it is applied.

These criticisms often arise from the practical challenges of designing for socio-technical systems, specifically, that design may not be able to grapple with the complexity of socio-technical system challenges. Researchers have thus proposed that systems thinking offers natural alignment to design and can be integrated as a way of orienting design towards more systemic approaches (Buchanan 2019; Jones and Kijima 2018; Sevaldson et al. 2010; Sevaldson and Ryan 2014). As seen earlier, systems thinking and design are complementary approaches, both being adopted by organisations when dealing with socio-technical systems and challenges and it is only natural that systems-led design has emerged.

Systems-Led Design for Socio-technical Engineering Systems

Systems-led design has emerged and is the intersection between systems thinking, design, and their practices (Ryan 2014; Sevaldson and Ryan 2014) to help practitioners undertake design related to complex, social systems (Jones 2014; Stolterman and Nelson 2012). Incorporating also a strong technical systems engineering core (for a review see also Sillitto et al. 2019), systems-led design builds further by emphasising systems thinking for designing socio-technical engineering systems. Systems-led design has emerged and been developed through integration of design research programmes at several universities participating in the Relating Systems and Design Symposium that sought to examine the intersection of systems theory and design practice (Jones and Kijima 2018). Systems-led design is an inquiry of action (Stolterman and Nelson 2012) that invites a diverse range of perspectives and approaches (Sevaldson and Jones 2019; Birger Sevaldson and Ryan 2014) such as soft systems and critical systems methodologies, system thinking skills and mindset (Costa Junior et al. 2018). According to Ryan, systems-led design values diversity in perspectives, integration between worldviews, collaboration with shared ownership and accountability, and the ability to address complex challenges within its broader context by being reflective about the self and the patterns of relationships (Ryan 2014). This flexible and methodologically pluralistic approach to systems-led design is important as it helps to minimise the risk of it being reduced to a formulaic process or set of tools.

By incorporating systemic ways of thinking into design practice, systems-led design is put forward to help designers better understand and deal with the complexity of the problem and systems they deal with (Lurås 2016; Ryan 2016; Birger Sevaldson 2013). It does this by helping designers:

1. Understand complex systems, and the context of that which is being designed.
2. Emphasise the connections and relationships within the system.
3. Include multiple perspectives.
4. Identify leverage points, which can help designers see opportunities and identify which interventions may have a significant impact (adapted from Lurås 2016).

These four propositions, along with the flexible and pluralistic approach of systems-led design, are important as they are intended to help overcome the criticisms of design as a practice in dealing with complex problems. These four propositions are further mapped onto the features of systems-led design approaches, as discussed below.

Current Approaches to Systems-Led Design

Several authors have put forward various approaches for the practice of systems-led design to help designers achieve the above propositions. Despite the range of terminology used to describe these approaches, for simplicity the term "systems-led design" will be used for this chapter as all of the approaches are concerned with the integration of design with systems thinking approaches.

While there are many specific approaches or permutations of systems-led design methodologies in the literature, broadly speaking they combine methodologies from design practice and systems thinking. They are all intended to be used for complex problems that have a level of ambiguity and uncertainty.

More specifically, systems-led design approaches contain common elements of the method:

- The method commences generally with enquiry into the purpose, vision, or orientation of the work to be done or the challenges involved
- There is a strong emphasis on exploration or understanding of the whole system, using tools and practices that allow designers to visualise, make sense of, and

reframe systems and the elements within them, particularly in how it relates to the challenge or issues at hand
- Then methods of systems-led design generally moves into an iterative, yet action-oriented approach to help identify, create, and catalyse opportunities for change into the system
- Methods generally also emphasise a feedback loop, to understand how implemented solutions start to shift the system, create ripple effects, change the way we understand the system or make impact. This also allows them to consider ways to adapt certain solutions or levers.

Generally systems led design practices in the literature include common elements:

- Principles or mindsets required to effectively use the practice
- Processes or approaches to carry out the practice in applied settings
- Methods or tools that can be utilised at different parts of the practice

Systems-led design practices all place importance on the principles and mindsets required to use systems-led design to deal with complex issues. To demonstrate the commonalities between these, core features of these elements of the following five frameworks will be explored:

- A systems-led design (also known as systemic design) framework by Ryan (2014), which has been applied within the Alberta CoLab.
- A systems-led design methodology (also known as systemic design) put forward by Jones (2014)
- Systems-oriented design methodology by Sevaldson (2013).
- A design system methodology for complex problems by ThinkPlace (Body and Terrey 2019).
- Design Council's Systemic Design Framework (Design Council 2021).

Core Features

A comparison of the core features of the five approaches is outlined in Table 3. In parentheses in the table cells, the association with the core features of design practice and systems thinking established earlier is also outlined. This mapping demonstrates that current, yet diverse, approaches to systems-led design in the literature do contain the core features of design practice and systems thinking. Therefore, they have been integrated in a way that has both emphasised systemic ways of thinking, while not losing the essence of designing.

To further investigate the synergies between systems thinking and design practice, the core features from the four approaches to systems-led design, including their comparison with the core features of systems thinking and design, were analysed and synthesised into six key principles and their related features. These are listed below in Table 4 and provide a simpler framework for study of a practical application of systems-led design.

Table 3 Comparison of systems-led design approaches

Ryan (2014)	Jones (2014)	Sevaldson -(Aguirre Ulloa 2020)	Body and Terrey (2019)	Design Council (2021)
Inquiring (collaborative and multidisciplinary) **Open** (collaborative and multidisciplinary) (consideration of multiple perspectives and the individuals' mental models that give rise to these perspectives) **Integrative** (whole systems, and how the parts within the system give rise to the whole) **Collaborative** (collaborative and multidisciplinary) (consideration of multiple perspectives and the individuals' mental models that give rise to these perspectives) **Centred** (whole systems, and how the parts within the system give rise to the whole	**Idealisation** (problem framing and solving) **Appreciating complexity [of systems]** (whole systems, and how the parts within the system give rise to the whole) **Purpose finding** (problem framing) **Boundary framing** (definition of the boundary of a system of interest, and the interrelationships of the parts (elements)) **Feedback coordination** (definition of the boundary of a system of interest, and the interrelationships of the parts (elements)) **System ordering** (dealing with complexity) **Generative emergence** (interconnections/interrelationships and dynamic behaviours) **Continuous adaptation** (iteration and experimentation) **Self-organisation** (consideration of multiple perspectives and the individuals' mental models that give rise to these perspectives) definition of the boundary of a system of interest, and the interrelationships of the parts (elements))	**Act proactively with complexity** (whole systems, and how the parts within the system give rise to the whole) **Co-design and co-understanding of the system** (collaborative and multidisciplinary) **Emphasise relationships** (definition of the boundary of a system of interest, and the interrelationships of the parts (elements)) **Toggle across different scales** (whole systems, and how the parts within the system give rise to the whole) **Leverage a range of interventions** (problem framing and solving) (iteration and experimentation) **Evaluate systemic consequences** (whole systems, and how the parts within the system give rise to the whole) (definition of the boundary of a system of interest, and the interrelationships of the parts (elements))	**Establish and clear intent** (problem framing and solving) **Take a human-centred approach** (empathy and focus on the human) **Collaboration and conversation** (collaborative and multidisciplinary) **Seek exploration and innovation** (iteration and experimentation) **Early prototyping** (iteration and experimentation) **Seek a balance of desirable, possible, and viable** (iteration and experimentation) **Design the whole system** (whole systems, and how the parts within the system give rise to the whole) (definition of the boundary of a system of interest, and the interrelationships of the parts (elements))	**Zooming in and out** (whole systems, and how the parts within the system give rise to the whole) **People and planet-centred** (empathy and focus on the human) (consideration of multiple perspectives and the individuals' mental models that give rise to these perspectives) **Testing and growing** (iteration and experimentation) **Circular and regenerative** (iteration and experimentation) **Inclusive and welcoming difference** (collaborative and multidisciplinary (empathy and focus on the human) **Collaborating and connecting** (collaborative and multidisciplinary)

Table 4 Synthesised principles and features of systems-led design

Principles and features	Opposing principle
Engage diversity of thinking Work with the right people at the right time to: Understand, represent, and consider diverse perspectives Promote discussion and feedback Be collaborative and tailored in your approach Ensure transparency of emerging systemic and design issues	**Participation is limited** to certain people who are easier to engage or conversations that are only supportive of current thinking
Build and maintain a shared understanding Articulate the collective vision of the change and its outcomes continuously, by asking and working through: What is the purpose? What is the system? The problem? The intent? Who is impacted? What is the current state of the system?	**The problem frame is narrow and not questioned** or developed by the designers only
Understand the whole, not just the parts Consider the broader context to: Understand the values, needs, goals, and behaviours and expectations of people at the Centre of the change Build a comprehensive understanding of the relevant context, including the environmental, systemic, and political Identify behaviours you need to change or influence Focus on the end to end experience Recognise and harness complexity and interconnections to identify opportunities for change Identify systemic factors to build, deliver, and embed change	**Apply reductionist or convergent-only thinking** to consider only components and develop narrow or well-determined solutions that do not consider wider context
Make connections between the user and the ecosystem Make connections between the user and the ecosystem to: Identify connections that may influence a change Consider other connections and their consequences Maintain connections that positively influence the designed change and its intended outcomes	**Overfocus on the user** without considering implications on the broader system
Embrace experimentation Test ideas, embrace risk, and be adaptable: Be open and transparent Move on from understanding the system by being action-oriented Gather information, reflect, and learn, to change course Learn and adjust existing progress to shape and iterate	**Implement solutions without experimentation** that are not iterated to consider the system, or are not innovative or shaped by an understanding of observation

Gaps in the Literature of Systems-Led Design

Systems-led design is still in its early stages and therefore it is unsurprising that there are theoretical and practical gaps in the field. Fundamentally, these relate to research on the effectiveness of systems-led design as a practice for designers dealing with complex problems, and the practical application of systems-led design, particularly within public sector contexts. For example, De Costa et al. (2019) noted that identifying strengths of different systemic approaches (for design) does not automatically create the perfect fit to handle real-world problem contexts, and therefore, further studies are required to test and validate frameworks associated with the practice of systems-led design. Malcolm (2017) also called for greater research to test advanced methodologies of systems thinking and systems-led design to support complex problems within public sector regulation.

Sevaldson and Ryan (2014) have also explained that systems thinking has not been successfully integrated into design because systems thinking has been perceived as too difficult or abstract. So, what is the challenge for the practical implementation of systems-led design? It is to help designers adopt systems thinking without losing the designerly practice, to use systems thinking to strengthen designers' relationships with complex problem situations. While Cabrera (2016) did note that deliberate use of systems thinking skills can help individuals embed such skills over time, studies focusing on this in relation to designers are less evident. For designers working with complex systems, adopting systems-led design as a practice is not only about their ability to use it, but also the factors in their environment that may influence the extent to which they are able to adopt and embed it. This calls for studying the implementation of systems-led design as a practice to identify what can enable designers to adopt systems thinking approaches in their practice.

Systems-Led Design in the Australian Taxation Office

To illustrate the practical application of systems-led design within the context of large-scale socio-technical engineering systems and to offer insight into the implementation of systems-led design, a summary and analysis of the implementation of the practice in an Australian government context is outlined below. The example demonstrates how systems-led design can both be applied to complex issues and systems as well as the challenges or considerations necessary to implement and embed in practice.

The Australian Tax Office (ATO) is a government organisation responsible for the administration of taxation and superannuation policies. Paying taxes is comparable to purchasing any other product or using any other service; however, the link between the taxes we pay and the goods and services we receive is less direct than most transactions people undertake (John Body 2008). However, the goods and services that citizens receive as a result of paying taxes are critical components of the society we live in and include things such as defence, policing, healthcare education, roads, infrastructure, and welfare programmes. The federal government largely depends on the taxation system to gain the revenue required to fund important economic and social systems and therefore needs to design effective administration of taxation policies.

The ATO is a large organisation consisting of over 20,000 staff and collects more than 95% of the federal government revenue, serving approximately 14.7 individual taxpayers as well as businesses. In the mid-1990s the ATO has sought new and contemporary approaches to administering an effective taxation system, including the use of design (Preston 2004). As such, Commissioner Trevor Boucher initiated a new vision that has since become a global example for design in government organisations and has continued to embed design into its culture and practice. The arrival of the Ralph Review in 1999 was another key driver, reinforcing the need for new approaches and initiating developments that saw design thinking employed in the organisation (Terrey 2012). This shift was led by design expert Richard Buchanan who was a member of a team of design mentors creating the design function in the ATO, soon after Buchanan released his "four orders" of design work in the early 1990s.

Body (2008) suggested three challenges for why the ATO became started to use design, namely:

- To better reflect the government's policy intent.
- To turn strategy into action.
- To make paying tax easier, cheaper, and more tailored.

Design has since been implemented and applied in different ways across the ATO with evolving models and governing structures. ATO has become recognised as a global leader in applying design as a large organisation, advocating for its use for over 20 years (Di Russo 2015). With a design function of approximately 70 designers, more recent evolutions of the practice have resulted in the ATO establishing a clear design process that is mandatory to be used for any large, proposed change (Di Russo 2015), aiming to not follow steps, but rather, to apply principles that are tailored to the project.

However, complexity in design practice for the ATO was primarily attributed to the relationships of stakeholders in the design process (Di Russo 2015). This could be the result of design in the ATO primarily being used to design complicated, narrow problems rather than broader or whole systems, such as implementation of a single legislative change or a process improvement (reference to verbal communication/interview conducted in 2019). To take this further argument further, design was unable to shift the organisation away from designing specific products, services or interactions that often-neglected broader context, towards designing within and for whole systems. Such issues align with the gaps and limitations outlined in the literature above. Given the ATO's role is to steward and administer on the whole taxation and superannuation systems, it is only sensible that the way it deals with socio-technical systems and its design practice evolves to incorporate systems thinking to most effectively do this.

As such, a decision was made to shift the design approach to a more systemic approach in 2019, to pioneer the adoption of systems-led design as the way it deals with complex problems. This sought to both address the practical issues it faced with its previous form of design and leverage the academic literature on the imperative and potential benefits of integrating systems-thinking into design.

The ATO developed its transdisciplinary systems-led design practice, named systems-led design as co-designed by staff, and released its systems-led guide in July 2020 (Kaur 2020). This practice is used by the ATO Design systems-led design practitioners, who assist the organisation to deal with complex problems. An outline of the practice is below.

The Systems-Led Design Model as Applied to the Australian Taxation Office

The model is a circular representation of the key phases the Australian Taxation Office (ATO) has adopted as part of its systems-led design framework. These phases are outlined in Fig. 1 below (ATO 2020).

The Systems-Led Design Principles as Applied to the Australian Taxation Office

In order to support practitioners in thinking differently and applying systems-led design in the intended way, a range of principles have been established (Fig. 2). Specifically, these are:

1. Engage diversity of thinking
2. Build and maintain a shared understanding
3. Understand the whole, not just the parts
4. Make connections between the user and the ecosystem
5. Embrace experimentation

Each principle includes additional detail to help designers understand more deeply the intent of the principle and to practically apply the principle. The principles are intended to support designers to bring a systems-led design mindset into their work and provide guard rails that ensure rigour of their practice yet enough flexibility to tailor approaches, methods, and tools to fit the specific initiative they are working on.

The Australian Taxation Office's (ATO) systems-led design frameworks embodies the principles and practice of systems thinking and design, bringing a discipline that is pluralistic and appropriate for the use of complex socio-technical systems. It has been applied to several challenges in the context of taxation and superannuation and serves as a good example of the use of systems thinking approaches is being applied to socio-technical systems.

Reflections on Applying Systems-Led Design in the Australian Taxation Office

While the Australian Taxation Office (ATO) has now implemented systems-led design as part of its design practice and broader governance for delivering large change, it is still a new practice and the ATO will continue to evolve it. It is promising to see that early sentiment obtained from a survey and focus groups indicate that designers in the ATO do think that the ATO's systems-led design framework is valuable for their work. Early insights gained from focus groups, a survey with the design practitioners, and stakeholder interviews are outlined below (Kaur 2021).

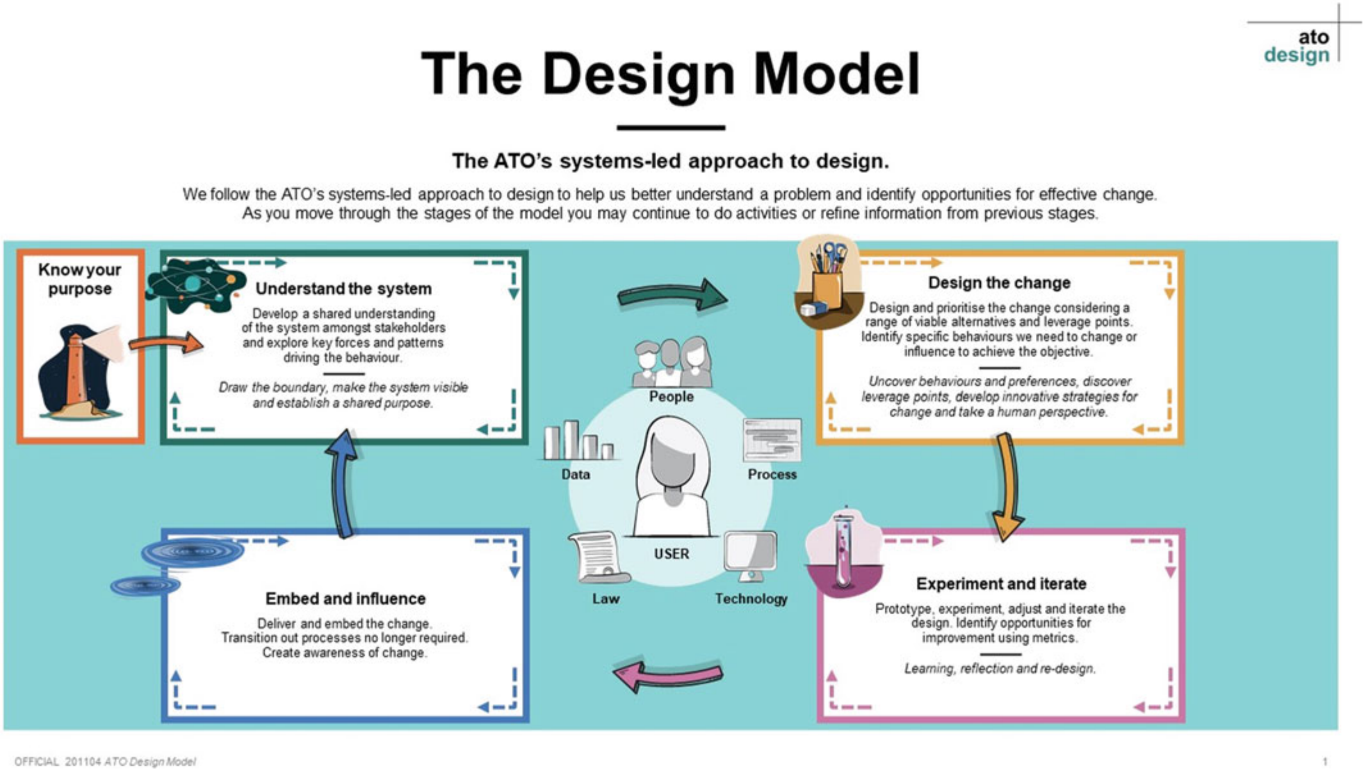

Fig. 1 Australian Taxation Office's (ATO) systems-led design model (ATO 2020)

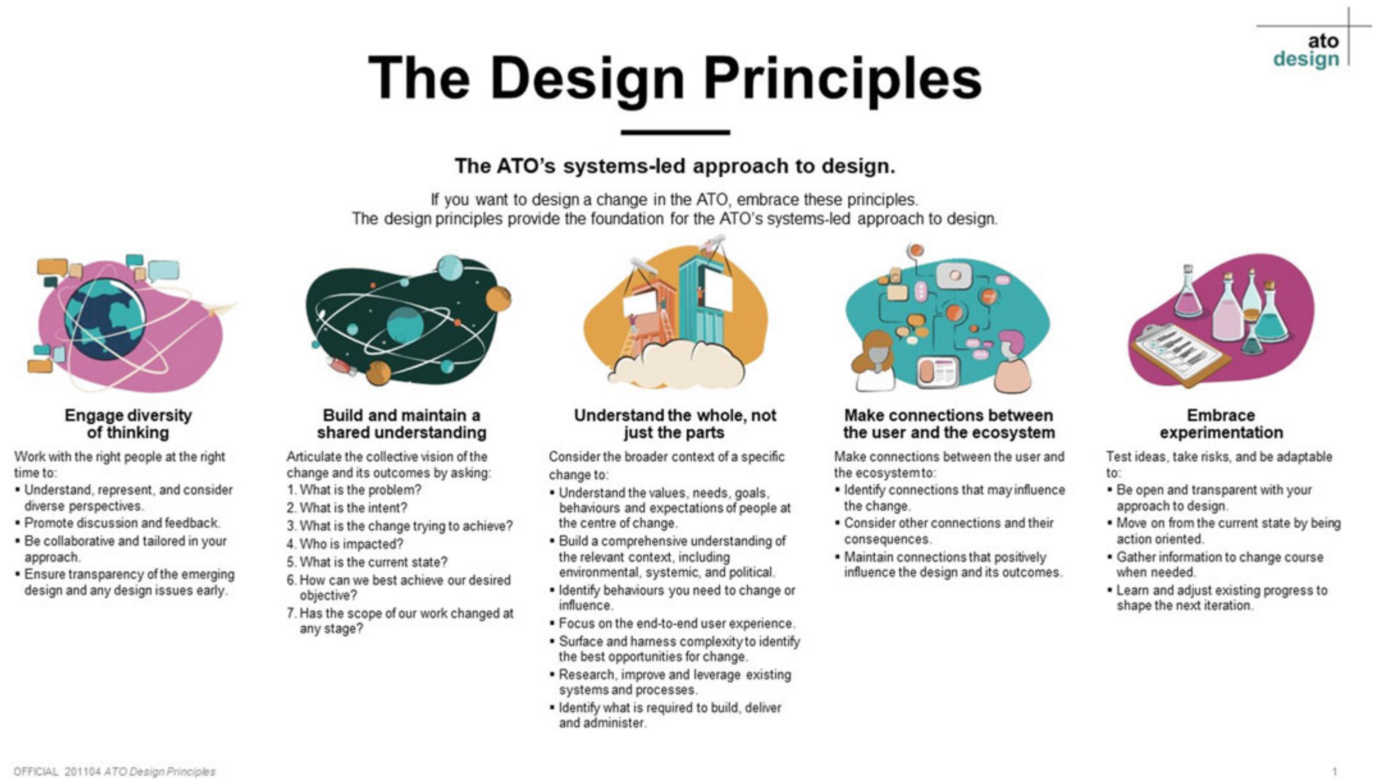

Fig. 2 Australian Taxation Office's (ATO) systems-led design principles (ATO 2020)

Systems-Led Design Is Flexible and Should Be Fit for Purpose

The literature recognises that systems-led design is not meant to be a rigid framework (Aguirre Ulloa 2020; Ryan 2014) and this reaffirms the importance of tailoring it in the design of an organisation's approach to it. One of the most notable insights that have been shared by designers is the recognition that this flexibility extends past the framework itself into how it is applied to projects. This reinforces the need to ensure that focus is placed on understanding the "purpose" of any design effort prior to developing an approach. While designers are still learning and building their capability and confidence in applying the ATO's systems-led design framework, anecdotal evidence suggests that there is growing confidence to experiment with approaches, methods, and tools within a project. This sets a foundation for ensuring the ATO does not reduce its practice to a formulaic or process-driven framework and the need to ensure practitioners do not take the framework or guide as prescriptive rules.

There Can Be Trade-Offs in the Framework

The ATO's designers find it easier to use the model over the principles as the primary guidance for the practice. While the reason for this is not yet clear, it could be because the principles are far less tangible, do not describe phases or a process, and trade-offs can be seen between them. The primary example of this is the principle of "engage diversity of thinking", which at times were found to be conflicting with "build and maintain a shared understanding" and "make connections between the user and the ecosystem". Designers reconciled this by ensuring that shared understanding was clear of the purpose and of the different perspectives in the system. Stakeholders did not have to have a single view or perspective; however, all the perspectives including the trade-off between these needed to be visible to everyone. Furthermore, while systems-led design does not focus on a single user, designers still felt that there was a difference between the user and other stakeholders when designing for the tax and super system, and while all perspectives should be acknowledged, there should still be additional focus on connecting the users to the broader ecosystem, including the perspectives of other stakeholders.

Systems-Led Design Is Most Useful for Complex Problems

One of the key challenges designers have identified in using systems-led design well is the ability to influence clients that the intensity and time it takes to undertake a project well is worth it and that designers should be engaged at the beginning of the work. This has raised discussions of when systems-led design should and should not be applied in organisations. While the principles of systems-led design can be applied to almost anything, undertaking the approach can be an intensive process and therefore may not be appropriate to be undertaken solely for efficiency gains, rather, it should be applied to complex problems that are hard to define, have multiple options for interventions, and involve a range of stakeholders. As Sevaldson (2017) notes, systems-led design practitioners can find that the approach can be intensive at the start of their practice; however, this time spent is often reducing risk and duplicated effort or prosecution of decisions later in the process.

The second consideration relevant here is the importance of building up an organisation's awareness and understanding of what systems-led design is, why and when it is used, and what the approach could look like and coupling this with designers' ability to engage with clients on the topic of systems-led design effectively in a way that resonates with them.

A Stronger Focus on the Whole System Is the Most Reported Shift

In describing what systems-led design is, how it is different to previous or other forms of design, and how it has changed the way designers have undertaken their work, the most prevalent shift centres on the theme of a more explicit focus on the whole system. Designers noted that they are more conscious of "zooming out" to consider the whole system and the elements within it and using this to consider how changes to the system could have flow on effects, how multiple changes may interact with each other, and how to discuss different levers and the trade-offs between these. This is further reinforced by the prevalence of systems maps, diagrams, or narratives, which has been an observable difference when compared to the design documentation of the Australian Taxation office (ATO) prior to the implementation of its systems-led design framework.

Conclusions

It is clear that systems thinking and systems-led design can help us understand and respond to complex phenomena and the challenges of working and intervening in socio-technical engineering systems. That said, they are not without their limitations. For some, these approaches might feel amorphous, overly principles-based, or theory in search of practice. There is no doubt that systems thinking can be difficult to operationalise and apply to the context of designing and intervening in complex systems. Our survey of the literature demonstrates that the systems and design communities are taking these challenges seriously in the way that these respective disciplines are being continually tested and refined. Just as we never "design" an entire engineering system, it is impossible to fully "design" the set of tools that engineering system designers have at their disposal. Instead, practitioners and academics will continue to modify and extend those tools that we already have, thinking strategically about how we can *redesign those* tools to move the field in the direction we want it to go.

In our own experience with developing an applying these tools in the Australian Taxation Office (ATO), there are a range of areas where we continue to be challenged and that form the foundation of future research or exploration. These include:

(a) How we design environments that promote continuous capability and knowledge building, so that practitioners have sufficient time and space for designers to reflect, learn, evaluate and share their experiences
(b) How we build awareness and understanding of the value of taking a systems-led approach at higher scales, so that it can be effectively implemented at lower ones

(c) How we reimagine or redesign organisations so that systems-led approaches are normal, not exceptional

Alongside these theoretical challenges, there is a clear need for further empirical work on the application of systems-led approaches in different societal contexts. The current body of research largely focuses on the theoretical foundations of systems-led design or the localised application of it on a project. This limited understanding can lead to the implementation of design for the wrong reasons, or unrealistic expectations of what systems-led design can achieve. Continued empirical work, with rich insights about practice, would serve as a starting point for practitioners, researchers, or government organisations looking to adopt systems-led design (Kaur 2021). These are the kind of insights we are going to need if our ambition is to understand and improve the ways that we design and manage the socio-technical engineering systems that make up our world.

Cross-References

► Asking Effective Questions: Awareness of Bias in Designerly Thinking
► Choosing Effective Means: Awareness of Bias in the Selection of Methods and Tools
► Design Perspectives, Theories, and Processes for Engineering Systems Design
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Part II

Describing Engineering Systems

Technical and Social Complexity

8

Babak Heydari and Paulien Herder

Contents

B. Heydari (✉)
College of Engineering and Network Science Institute, Northeastern University, Boston, MA, USA
e-mail: heydari@northeastern.edu

P. Herder
Faculty of Applied Sciences, TU Delft, The Netherlands
e-mail: p.m.herder@tudelft.nl

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Abstract

In this chapter, we will argue that identifying and analysing the key *drivers* of complexity – within and outside of systems – is generally more useful than trying to find universal definitions and measures. Focusing on the key drivers enables us to identify and evaluate system-level trade-offs and equip us with leverage points that can enable engineering methods to manage system complexity. We will discuss two of the main drivers of complexity: increased interconnectedness amongst systems constituents (network complexity) and multi-level decision-making (multi-agent complexity). These two forces are natural consequences of advances in information and communication technology, and artificial intelligence on the one hand, and changes in the architecture of socio-technical engineering systems that have given rise to open, multi-sided platform systems. As a natural consequence of focusing on complexity drivers, we argue for a shift in perspective, from *complexity reduction* to *complexity management*. Moreover, in most complex socio-technical engineering systems, managing complexity requires adopting a lens of system *governance* – as opposed to conventional engineering design lens – whose goal is to steer the emergent behaviour of the system through a combination of incentive and architecture design. We will argue that to properly manage complexity, the engineering system and its governance structures need to be designed in an integrated fashion, instead of consecutively. We will further argue that proper integration of AI into engineering systems can play a significant role in managing complexity and effective governance of such systems.

Keywords

Complexity · Emergence · Engineering systems · Governance · Management · Modelling

Introduction

Complexity has been an increasingly important topic in engineering systems over the last two decades. Increased complexity of engineering systems has often been used to motivate engineers to adopt systems thinking and holistic approach. Studying complexity has also been a cornerstone of a growing interdisciplinary approach in systems engineering and has worked as an umbrella construct that has brought together perspectives from complexity sciences, social and economics sciences, and engineering design sciences.

On top of this ongoing integration, the rapid rise of artificial intelligence (AI) and automation, abundance of dynamic behavioral data, and the prospect of Internet of Things (IoT) further emphasize the significance of adopting a sociotechnical complexity perspective. Beside transforming a wide range of industries, these technological advances call for integrating the analysis, design, and governance of the social and technical sides of future complex engineering systems, thus demanding an *integrated approach towards dealing with technical and social complexity*. Such demand is chiefly a response to at least three challenges: First, the rise of AI in many engineering systems, often through inclusion of more than one decision-making automated agent (multi-agent systems), means that the technical side and the social side of the complex systems *coevolve* with each other throughout the system life cycle. Governing this co-evolution is largely ignored in traditional engineering design. Second, increased scale and speed of access to dynamic behavioural data on social preferences, consumption patterns, demand changes, and market norms and sentiments enables their integration into the system and product design and management process. Third, there is abundant literature in organizational behaviour and management science that suggest a strong mutual influence of the structure and performance of the governance model (e.g., design teams and organization architecture) with the product architecture. In light of such trends, we need to understand and manage socio-technical complexity of engineering systems, as well as the complexity profile of the broader context in which these systems are designed, operated, and governed.

But what *is* complexity? How can we define and measure it? How can we reduce it? Before trying to answer these questions, it is worth pausing to ponder and see whether we are asking the right questions here when we set such goals – that is, to define, measure, and reduce complexity. What have we achieved from pursuing such goals in more than 40 years since the formal introduction of complexity sciences? What are the alternative approaches towards systems complexity in the engineering design context? This chapter proposes a different set of questions: What can systems engineers *do* with the complexity concept and how can they manage it? And, what are the implications of advances in artificial intelligence and prevalence of multi-sided platforms in systems' complexity and our available methods to govern them?

These are important questions that deserve a comprehensive review of – and reflection on – existing literature and, in some cases, conducting original research. Rather than taking a fully comprehensive approach – which can easily turn into a whole new book by itself – the goal of this chapter is to underline the significance of some of these questions, discuss different approaches towards complexity and its management that are available to system designers, and offer some perspectives on future directions in this area.

While technical and social complexities have sometimes been treated separately, and in some cases in different literature, in this chapter, we will argue that such distinctions are less appropriate for modern engineering systems where the lines between drivers and management mechanisms of technical and social complexity have been blurred. Instead, we will take a socio-technical approach towards engineering systems complexity and will emphasize each factor when appropriate within each section. Besides semantic difficulties to separate the two domains, this approach follows one of the central themes of this chapter, that is, the engineering system and its governance structures need to be designed in an integrated fashion, instead of consecutively.

Complexity in Engineering Systems

From Definitions to Drivers

Complexity is an elusive concept! For many years, the list of definitions of complexity and ways to quantify it was growing as fast as the complexity of the systems they were trying to characterize. This effort that was started with the rise of complexity science led by the Santa Fe Institute in the 1990s (see (Holland 2006; Gell-Mann 1995; Axelrod et al. 2001) for discussions on foundations of complexity sciences by some of the founding fathers of the field) continued by the systems engineering community who was facing new challenges that were not solvable, using traditional systems engineering paradigms and frameworks (Bar-Yam 2003; Rouse 2003; Ottino 2004). The field needed novel scientific foundations, and the science of complexity seemed to be a great candidate to provide such foundation. Complexity then started to appear in the titles of the papers, themes of the conferences in the field, and students' research interest statements, and characterizing complexity was a first step in many of these areas.

Efforts to characterize complexity can be divided into four broad categories: (1) constructing general – and in some cases universal – definitions for complexity; (2) quantifying and measuring complexity of a given system; (3) identifying a network of similarities in complex systems; and (4) identifying the key drivers of complexity. The first two categories are in response to the first two questions raised in the previous section (what is complexity? and how to measure it?) and are closely related to each other. They collectively have received most of the attention, generating a diverse set of perspectives that further lead to a secondary group of publications on taxonomies on definitions and measures of complexity (see Chap. 7 of (Mitchell 2009) for an excellent review; also see (Kreimeyer and Lindemann 2011; Ladyman et al. 2013; Mina et al. 2006; Magee and de Weck 2002)). In a widely referenced paper, Seth Lloyd (2001) divided the suggested measures of complexity in the literature into three broad categories based on the level of *difficulty in description*, typically measured in bits (e.g., entropy, algorithmic complexity, fractal dimension); level of *difficulty in creation*, typically is measured in time, energy, or dollars (e.g., computational complexity, logical depth, cost); and the *degree of organization* in the systems, which is further divided into two subcategories of effective complexity and mutual information. Similar efforts – although in a smaller scale – have been suggested for complexity definitions, where the focus shifts from quantifying complexity to identifying its sources (Table 1). In (Wade and Heydari 2014), for example, the authors divide the definitions into three classes of *behavioural*, based on treating the system as a black box and characterizing complexity solely based on the system's output (e.g., complexity attributed to a multidisciplinary team of system designers); *structural*, based on the number of parts and their interaction patterns (e.g., complexity of an e-commerce supply-chain system); and *constructive*, based on the difficulty in determining the future outputs (e.g., complexity of predicting future states of interaction between a human agent and an reinforcement learning agent).

Some authors believe that the ambitious goal of finding a unified theory for complexity that has been a major driving force behind the first two lines of efforts (i.e., defining and measuring complexity) described earlier has not fulfilled its intended goals (see Horgan 1995) for some critical perspectives on complexity science), and more importantly, when it comes to the *engineering* perspective, it appears that the scattered set of complexity definitions and measures have achieved little that can be used to more effective design and operation of complex engineering

Table 1 Categories of complexity measures (Based on Lloyd 2001)

Measure category	Key question	Examples	Common units of measurement
Description-based	How hard is the system to describe?	Shannon entropy, Fisher information, algorithmic complexity, fractal dimension	Bits
Creation-based measures	How hard is it to create the system?	Cost, computational complexity, thermodynamic depth	Dollars, time, energy, etc.
Effective complexity	How hard is it to describe organizational structure?	Static complex network measures, conditional information, hierarchical complexity, grammatical complexity	Graph-based measures such as degree distribution, centrality measures, modularity, etc., bits
Mutual information	How much information is shared between different system's parts?	Mutual information, dynamic complex network measures	Correlations, information sharing cost and benefits, bits

systems (De Weck et al. 2011). However, the next two lines of efforts (i.e., establishing networks of similarities and driving forces), although less ambitious compared to the first two, are more realistic – and can be more helpful. In transitioning from an effort to find a unified perspective of complexity to a set of common features and key drivers of complex systems, we follow the lead of Ludwig Wittgenstein in his discussion of the concept and meaning of *games,* in his book, *Philosophical Investigations*. There, after pointing to problems with different common definitions of the term as an illustrative example, he proceeds to claim that there is no characteristic that is common to everything that we call games. Instead, he suggests that the meaning of the word can be best understood through a *network of similarities and relationships* (Wittgenstein 2009).

This approach calls for putting more emphasis on the last two lines of effort mentioned earlier, namely, identifying the common characteristics of complex engineering systems and – more importantly – the key forces behind complexity in such systems. While the first line of effort is most useful in building empirical taxonomies for complex systems (Sheard and Mostashari 2009; Bar-Yam 2002), we argue that it is the second line that is more helpful for identifying and evaluating fundamental systemic trade-offs and detecting leverage points that can be used in *managing complexity* for socio-technical engineering systems (Manson 2001; Helbing 2007; Espejo and Reyes 2011; De Weck et al. 2011) (see the section on Managing Complexity in Engineering Systems). Moreover, and to use a linear algebraic analogy, key drivers of complexity can be thought of as the *eigenvectors of complexity* for systems, which provide us with a smaller set of elements to work with, compared to what we often face when we list the common features of complex systems. Finally, focusing on drivers of complexity enables us to better link the engineering perspective to some powerful bottom-up modelling and simulation methodologies such as agent-based simulation (Bonabeau 2002*;* North and Macal 2007*;* Van Dam et al. 2012).

We will argue that many important forms of complexity we encounter in socio-technical engineering systems can be attributed to two underlying drivers: changes in system *interconnectedness* and changes in system-level agency and *decision-making authorities*. This is a much shorter list compared to larger sets of common attributes of complex systems in the literature. However, many of those attributes can be linked to one or a combination of these fundamental forces. For example, an increase in interconnectivity level of a system (at the physical or decision level) gives rise to higher levels of non-linearity in system's behaviour, a common attribute of many complex systems. Presence of some form or *emergent property* is another common attribute that can be linked to one or a combination of these two forces, as will be discussed in a separate subsection. Similar arguments can be made about other attributes such as size, heterogeneity, and entropy (Pincus 1995; Zurek 2018; Page 2010), chaotic order (Lewin 1999), and self-organization (Comfort 1994; Schweitzer 1997), although we will not discuss all these connections in this chapter.

In what follows, we briefly discuss the role of each of these drivers. It is worth mentioning that traditionally, interconnectedness contributed more to technical complexity, while decentralized autonomy contributed to social and organizational complexity. As argued earlier, however, the line between the two types of complexities has been blurring, and in most modern engineering systems, both factors interact and contribute to socio-technical complexity.

Complexity and System Interconnectedness

In a world dominated by online social media, a fast-spreading pandemic that took over much of the globe in a few months, global platforms for applications such as higher education and gaming, and giant scale open-source engineering projects, interconnectedness is not an abstract concept. For several decades, the *butterfly effect* (Gleick 2011) was the epitome of how certain local events with small magnitude can quickly become global and show massive ramifications. Butterfly effect is now a part of our daily life, however, and today, we can point to tangible real-world examples where local small-scale events have quickly resulted in large-scale system-level changes: in the form of pandemics (COVID-19), regional uprising and political shifts (Early 2010s Arab uprising, started by a Tunisian street seller), and spread of disinformation with significant global political consequences (Brexit and American 2016 Election).

When it comes to interconnectedness and complexity, we take a dynamic approach and are primarily interested in three questions: First, we are interested to know *conditions under which systems tend to become more interconnected*. Second, we would like to know *why and how an increase in interconnectedness impacts complexity.* Finally, since in most engineering systems, internal connections are multi-level (connecting different levels of hierarchy) and multi-modal (related to different types of transactions), we need to distinguish between *various types of interconnectedness and their differences* when it comes to their impacts on complexity.

We start with the first question: *Why have we seen a dramatic increase in the level of interconnectedness in various systems in recent decades?* From a systems science, context-independent perspective, we can identify two interdependent factors: The first factor has been an exponential decrease in different forms of connection costs – what institutional economists refer to as transaction cost (Williamson 1979; Langlois 1992) – for exchanging different forms of resources (physical, social, information, and energy) across otherwise disjoint systems' constituents. This decrease in cost, in conjunction with benefits of connectivity that are accrued from a wider access to more diverse pool of resources, translates into a systemic factor that contributes to the exponential increase in systems' interconnectedness. Second, these benefits are further boosted by advances in distributed data-collection technologies (such as advanced sensors), further amplifying those interconnectivity forces (see (Mosleh et al. 2016a) for a more comprehensive discussion on this dynamic).

What types of interconnectedness are more crucial in analysing and managing socio-technical engineering systems complexity? Here, we can distinguish between three types of bonds that link different parts of systems to each other: physical resources, information (Gharajedaghi 2011), and risk (Helbing 2013). The first type includes links that facilitate exchange of energy and materials and is the main source of interconnectedness in traditional engineering systems such as cameras, cars, and chemical plants. The other two categories are more crucial in socio-technical engineering systems. In such systems, new connections are constantly created between different systems – or different parts of a given system – to enable access to information that is not locally available. For example, new connections between actors in and outside of the system will continuously form, change, or disappear. Such links are multi-level and multi-modal: Organizational hierarchies are abolished or formed during the design process or during the system's operational life, information is exchanged more quickly amongst actors, and new actors enter the arena, while other actors may leave (Mosleh et al. 2016a; De Bruijn and Herder 2009; Heijnen et al. 2020). Both physical and information links can then change the risk profile of systems and create what is often known as systemic risk, a concept that gained popularity following the 2008 financial crisis (Acemoglu et al. 2015; Eisenberg and Noe 2001) and was later adopted for a range of other applications (Beale et al. 2011; Chen et al. 2013).

Complexity and Multi-Level Decision-Making: Distribution and Composition of Autonomy

Unlike interconnectedness, which has been a key contributing factor to systems complexity in engineering for a long time, this factor has traditionally been a primary concern for organizational scientists and institutional economists, where the distribution of decision authority amongst different humans or organizations and the subsequent complexities due to challenges regarding coordination, cooperation, and effective communication of such authorizes have long been an active area of research.

Although this line of thinking has been pursued by scholars in different disciplines, it has arguably been most developed by institutional economists in the last century. Interestingly, the term, institutional economics, was first coined by Walton Hale Hamilton in 1919 (Hamilton 1919), in part as an effort to incorporate the issue of institutional-level control with models of human behaviour under the same theoretical foundation: "The exercise of control involves human activity and leaves its mark in the changed activity of others. Institutions, seemingly such rigid and material things, are merely conventional methods of behaviour on the part of various groups or of persons in various situations" (Hamilton 1919). This line of thinking was later further developed and rigorously formulated by the pioneers of new institutional economics such as Ronald Coase, Douglass North, Mancur Olson, Oliver Williamson, and Elinor Ostrom, the latter two shared the Nobel Memorial Prize in Economic Science in 2009. Methods and insights generated in this literature on issue such as boundaries of organizations, role of transaction costs, modes of governance, models of bounded rationality, and information asymmetry can be used by system designers, not just in design and governance of engineering organizations and institutions, but also in designing multi-agent socio-technical systems, where presence of AI agents creates new forms of system complexity and consequent challenges, as described earlier in this chapter.

Similar to what we pursued regarding system interconnectedness and the forces that result in changes in that factor, it is also insightful here to first think about the reason systems move away from the simplicity of centralized decision-making schemes, despite all the challenges that are associated with design and governance of multi-agent complex systems (Kim and Zhong 2017).

The short answer is that centralized decision-making can be extremely difficult or impossible, because of the scale, complexity, and environmental uncertainty of many engineering systems (Zeigler 1990; Barber et al. 2000; Ota 2006). In most cases, system-level decisions are in the form of dynamic resource planning that allocate different forms of resources (energy, materials, information, security, etc.) to different sub-systems. Attempts to manage all decision-makings centrally, by gathering information from widely dispersed system components and then broadcasting decisions back to those components, can lead to inefficient systems since they become slow in responding to changes in their environments. This inefficiency gets aggravated by the heterogeneity level within the engineering system on the one hand, and the scale of changes in its environment on the other, which in turn will make pre-planning – based on anticipation of changes – more challenging. To response to these challenges, the system can provide two layers of decision-making authorities to the lower-level constituents: first, delegate parts of resource planning decisions to sub-systems. Second, enable these constituents to communicate and exchange resources. Both these mechanisms increase systems' adaptability and resilience by accommodating unexpected changes in the environment and ensuring a more efficient allocation of resources (Mosleh et al. 2016a). By incorporating these two schemes of distributed autonomy, the system creates some form of *internal market mechanism* with the goal of more efficient resource allocation in response to changes in the environment.

The confluence of these factors that favour distributed autonomy for certain types of engineering systems, and the development of more powerful hardware and algorithms to implement effective autonomy have given rise to their applications in many engineering systems, including in robotics, transportation systems, energy systems and smart grid, cloud computing, security, satellite systems, communication networks, aviation, and security (for surveys on these applications and some underlying theoretical foundations, refer to (Dorri et al. 2018; González-Briones et al. 2018; Dominguez and Cannella 2020)).

Following the theme of this chapter, the next natural question is on the effect of different schemes of decentralized autonomy on system complexity. Here, we offer three factors that influence system complexity:

1. *Number of autonomous decision-making entities (agents)*: All other things being equal, we expect system's complexity to increase with the number of autonomous agents. This is mainly due to an increase need of coordination and different conflict resolution mechanisms amongst agents.
2. *Distribution of authority across these agents and the level of strategic alignment*: For a given number of agents, we expect the complexity to depend on the scale of tension amongst their goals and objectives. Fully aligned objectives or zero-sum goals – the two extreme cases – are often rare in engineering systems and in most systems, we face a mixture of cooperation and competition amongst constituents. We expect system complexity to increase as the level of strategic alignment between agents decreases and as cooperative interactions become harder to achieve.
3. *Structure of interaction and resource exchange amongst agents*: Structure shapes behaviour, and this is truer for multi-agent where system-level behaviour is the aggregate result of local behaviours. As discussed earlier, enabling local resource exchange amongst agents is one of the main reasons for adopting decentralized autonomy in engineering systems. Consequently, we expect the interaction structure of agents to have a direct impact on system's complexity. Many factors such as system-level boundaries of local vs. global (who to share resources with), incentives to cooperate and compete, and efficiency of information access depend on the structure of agent to agent interactions. This factor – interaction structure of decision-making constituents of a system – falls in the overlap between the two drivers of complexity (interdependence and autonomy) and acts as a bridge between the two.

Combining the Two Forces: Interconnected Design Decisions

Interconnected design decisions are relevant to most factors we discussed earlier: They are formed to facilitate exchange of physical and information resources, to balance risk at the system level, and have implications for complexity of the system as well as its social and organizational context. Moreover, the design process by a team of designers for a system with interconnected design decision incorporates the role of both agency-driven complexity and interconnectedness-driven complexity, key drivers of complexity we presented in this chapter.

Design of engineering systems can be considered as a sequential search process (March and Simon 1958) whose goal is to identify solutions that are superior to what is already known. It is crucial to differentiate between this sequential search process, reserved for large-scale, complex problems, and the conventional optimization process that is often used for simpler settings. This distinction is primarily the result of interdependence amongst different decision variables, which creates a rugged performance landscape that defies attempts to use common optimization techniques (Rivkin 2000).

The relationship between complexity and interdependent design decision variables (DVs) can be explored at two levels. The first level – easier to model and quantify – is the degree of interdependence amongst decision variables that can be defined as the average number of other influencing decision variables that can determine the *optimal* solution for a particular DV. For a given number of decision variables, we expect the complexity – and the ruggedness of the performance landscape – to increase, as the degree of interdependence rises. Like other metrics that rely on averages, one can build a simple stylized framework to capture the link between DV interdependencies and the ruggedness of performance landscape. Such a stylized framework – the so-called NK model – was first developed by the biologist and complexity scientist, Stuart Kauffman in the late 1980s (Kauffman and Levin 1987) in the context of evolutionary biology, and was later used in a variety of other fields, especially in management and strategy science literature (Levinthal 1997) (for a survey of management and organization science applications of the NK model, refer to (Baumann et al. 2019)). In its basic form, the model assumes N binary decision variables, each assigned a fitness function, and the overall performance of the system is the average fitness of all DVs. However, and in order to model interdependencies, the fitness of each DV is a function of its own value, as well as the value of K other DVs, selected from the rest of N-1 DVs. Consider a design problem with 100 DVs, with $K = 0$: The overall solution can be simply optimized by performing 100 independent binary searches, resulting in 200 trials. On the other end of the spectrum, a value of $K = 99$ means that more than 10^{30} solutions need to be analysed in order to find the *optimal* solution, which clearly is impractical! NK model quantifies this intuition by mapping the value of K to the level of ruggedness in the performance landscape (Fig. 1). Low values of K give rise to fewer number of peaks (only one peak for $K = 0$), which suggest that local searches are more likely to result in finding the global peak, irrespective of the initial solution, whereas higher values of K generate a large number of local peaks, making local searches less effective and making the success a strong function of the initial solution. The NK landscape layer is often combined with a second layer that models the behaviour of searching agents (designers) that can change the solutions in increments or in long jumps; communicate and learn from each other; balance exploration and exploitation; and work in subsets of decision variables. Some of the simulation-based

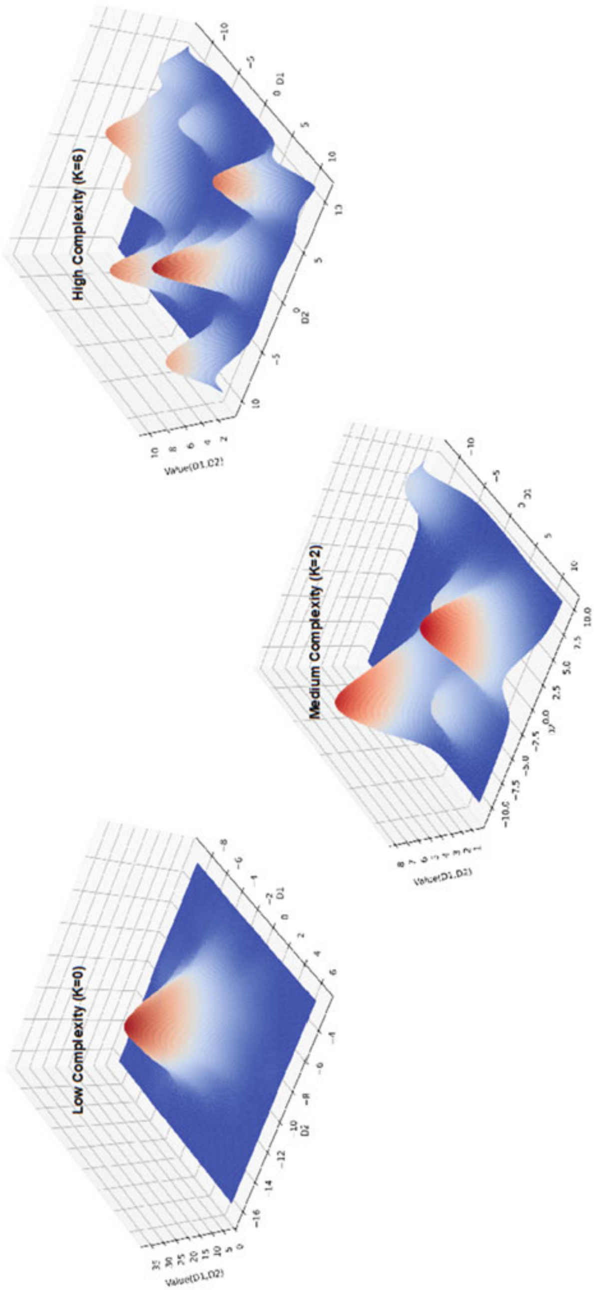

Fig. 1 Search Landscape for different complexity levels for a system with ten decision variables, along two of those variables

heuristics that are generated by using these two layers can be of direct use in design of engineering systems. Examples are the use of NK model in centralization vs. decentralization, division of labour, coordination and cooperation, modularity and innovation, product development, and team staffing.

Average number of interdependencies is not the only factor that impacts the difficulty of search on a rugged landscape. For a given average interdependency, the structure of links across different DVs can also play a significant role in various engineering systems design decisions such as system decomposition (Browning 2001), staffing (Colfer and Baldwin 2010), communication protocols across different teams (Heydari et al. 2019), and allocation of exploration vs. exploitation within a design organization (Lazer and Friedman 2007). Furthermore, a crucial step in architecting complex engineering systems is identifying modules and designing proper interfaces between them – which in turn will change the structure of certain decision interdependencies (Baldwin and Clark 2000). Finally, models based on NK method can leverage the existing literatures on design structure matrix (Eppinger and Browning 2012) – a rich literature well familiar to engineering systems design researchers – and network science, a vast and growing field that has already been used in different areas of engineering system design research (Parraguez and Maier 2016; Chen et al. 2018).

Emergence and Socio-technical Complexity Drivers

Brief Introduction to Emergence

Emergence is often described as one of the most fundamental characteristics of complex systems, to the extent that some authors have suggested defining complex systems based on presence of emergent properties. The idea that in some situations, the whole is more than the sum of parts, is an ancient idea and dates back to the time of Aristotle and his response to Zeno's paradox who pointed to conditions where "the totality is not [. . . .] a mere heap, but the whole is something besides the parts" [Metaphysics (Aristotle), Book H 1045a 8–10]. The concept has been a subject of numerous conceptual and formal definitions, classifications, and occasional controversies since the 1990s following the rise of complexity science. Similar to complexity, it is unlikely to converge on a single definition for emergence. Instead, from the engineering system design perspective, we are mainly interested in the answer to the following questions: *What are some key properties of emergent phenomena? Why do we need to care about emergence in complex engineering systems? And how can we include emergence in analysis and design of such systems?*

What is common in most definitions of emergence is *formation of novel macro-level structural, functional, or behavioural patterns, as a result of interactive dynamics at micro-levels*. Here, terms such as novel, macro, and micro are all relative and context dependent: The degree of novelty falls on a spectrum based on how much of the properties of the rising pattern can be directly broken down into the properties of the constituents at the lower levels. Micro and macro also refer to lower and higher levels of abstractions relative to each other. Moreover, emergent phenomena may be characterized independently (independent of their implementations) (Abbott 2006), something with notable implications for engineering systems, as we will discuss later.

Emergence in Non-linear and Multi-Agent Systems: Behavioural and Structural

We furtherneed to distinguish between emergent properties that are caused by *lower-level non-linearities*, and those caused by *interdependent choices in* multi-agent systems. Examples of emergent phenomena caused by non-linearities are liquid characteristics of water stemming from (non-linear) characteristics of hydrogen and oxygen chemical bonds, or solid-state circuit oscillators based on leveraging properly designed positive feedback loops. Emergence in multi-agent systems, on the other hand, is the result of aggregate repeated choices of a number of utility (fitness) maximizing agents who make – often evolving – interdependent decisions. Emergence in the latter sense can be formulated as a game-theoretic construct in the form of equilibria or dynamic trajectories towards an equilibrium. Nash equilibrium is the most common equilibrium concept, although not necessarily the most useful one for all applications (see (Halpern 2008) for a survey of some other equilibrium concepts). One key feature of multi-agent systems that has important engineering repercussions is the possibility of multiple self-reinforcing equilibria, even in simple setups with two agents, each with two actions (e.g., coordination games). In more realistic scenarios involving larger number of agents and larger action sets, thousands of equilibria might be possible, adding further complexity to the system (see (Zeigler 1990; Barber et al. 2000) for a technical discussion of such cases).

Many examples of the latter form of emergence can be found in economic and sociocultural systems. Different social and organizational norms can be considered as emergent properties, arising from micro-level game-theoretic interactions amongst agents. Several of these norms such as cooperation (Nowak 2006; Gianetto and Heydari 2013), competition (Gianetto et al. 2018), trust (Gianetto and Heydari 2016), fairness (Mosleh and Heydari 2017), and other altruistic norms are studied using evolutionary game theoretic methods (Sigmund 2010) in conjunction with agent-based simulation (Gotts et al. 2003). Although originally developed for applications in social sciences, this perspective of emergence is becoming increasingly widespread in socio-technical engineering systems, thanks to the dominance of multi-sided platforms in different domains, as well as advances in artificial intelligence. Take the introduction of front-facing camera to the fourth-generation of iPhone in 2010. Its introductionquickly gave rise to the popularity of *selfie* and a cluster of sociocultural norms around it, making selfie the word of the year by the Oxford dictionary in 2013. Introduction of the *share* option in Facebook or the *retweet* feature in Twitter are other examples that enabled – in addition to some positive consequences – an ecosystem of large-scale, fast-paced spread of misinformation with large-scale social and political ramifications.

As we will argue further in the next section, this distinction between two different forms of emergence is a more useful classification for engineering and policy purposes, compared to what has been suggested by some authors based on categorizing emergent properties as structural, functional, and behavioural. However, to create a loose connection between the two classifications, we can argue that system non-linearities cause structural and functional – but not behavioural – emergence, while interdependent choices are capable of creating all three categories. Besides behavioural emergence as discussed earlier, understanding and modelling structural emergence is crucial for many complex systems. Schelling segregation model (Schelling 1971) and the scale-free networks (Barabási and Albert 1999) are two classic examples where higher-level structural forms emerge from lower-level choices by the agents. Game-theoretic models have also been successful in modelling emergence of some common socio-technical structures such as modularity (Heydari and Dalili 2013) and core-periphery architectures (Heydari et al. 2015).

Engineering Systems and Emergence: Where and How Does It Matter?

Studying emergence in engineering systems is crucial from at least three perspectives: First, most system-level requirements are variations of emergent properties when presented at the highest level of description. Consider high-level requirements for a car voice control interface, which are often described as being able to understand and communicate with human agents in a natural lanuague. Being *natural* can be considered a property that emerges from lower level algorithms, engineered to produce a certain degree of similarity to human-level performance. Although this is common to some extent across all engineering activities, system designers tend to work more with high-level requirements that can be characterized as emergent properties. This is especially notable when we are concerned about the so-called system-level “-ilities”, such as flexibility, adaptability (De Weck et al. 2012; McManus et al. 2007), or some other system-level concepts such as resilience (Hosseini et al. 2016; Jackson and Ferris 2013) and modularity (Heydari et al. 2015; Solé and Valverde 2008). More generally, when we consider complex socio-technical engineering systems from the perspective of a policy maker or a systems engineer, one question of interest is usually along the line of “how can I adjust the factors under my control to achieve a desired outcome, often at a higher level of abstraction?”

The distinction we discussed earlier between emergence stemming from non-linearity, versus emergence in multi-agent setups becomes crucial in how to tackle the question above. In traditional engineering systems, the desired emergent state can be achieved by understanding the science and sources of underlying non-linearities and developing reliable modelling and simulation environments that can aggregate the effect of such non-linearities. Successful implementation of these steps can be credited as one of the key enablers of some notable engineering successes in the last century, from aircrafts to large-scale integrated circuits.

Dealing with decision-driven emergence in multi-agent systems requires a perspective shift, from the classical lens of control and optimization towards the new lens of *system governance* (Duit and Galaz 2008; Gorwa 2019; Keating et al. 2014). Here, system governance is closely linked to the notion of *design* perspective, which is referred to by J. Gharachedaghi as the third generation of systems thinking (Gharajedaghi 2011) that follows the first two generations driven by Operation Research and Cybernetics/Open Systems, respectively. The emphasis on design thinking is in the spirit of (Churchman 1971) who argues that the best way to *learn* a system is to design it and that the designers tend to choose the future rather than predicting it (Gharajedaghi and Ackoff 1984). These authors advocate using the term design, primarily for the management science community; however, for engineering systems, we advocate using system governance, since the term design is used for all forms of engineering activities and can lead to trivialization of the proposed perspective. System governance is discussed in more details in the *Complexity Management* section.

Managing Complexity in Engineering Systems

A deep understanding of fundamental drivers of complexity leads us to the next step, that is effective complexity management methods. As noted earlier, our goal in complexity management is not necessarily to eliminate complexity – some complexity is needed to satisfy systems' requirements, to make the system more adaptable, evolvable, resilient, and facilitate more efficient flow of system-level resources.

This perspective leads to a follow-up question: What is the *right* level of complexity for a given system? Answering this question can get us back to the labyrinth of complexity measures, something we already argued we want to avoid. Instead, a practical approach for complexity management is to relate some of the design leverages in complex systems to the key drivers of complexity and relevant technology trends. Before doing that, however, it is useful to briefly review the law of requisite variety that captures the intuition behind the *right level of complexity*. This will be followed by a discussion on some common complexity management mechanism through architecture, system governance, and the implications of artificial intelligence in system's complexity management.

Law of Requisite Variety

That the system's complexity needs to be proportional to the complexity of what is being controlled was first proposed by W. Ross Ashby, one of the pioneers of cybernetics in the 1950s. He maintained that for a system to remain stable, the number of states (*varieties*, in Ashby's term) in the controller needs to be at least equal to the number of the states in what is being controlled. In his words, "if a certain quantity of disturbance is prevented by a regulator from reaching some essential variables, then that regulator must be capable of exerting at least that quantity of selection. [. . . .] A system has good control if and only if the dependent variables remain the same even when the independent variables or the state function have changed" (Ashby 2013).

Although not directly formulated in the language of complexity, the law of requisite variety is useful in understanding the relationship between the complexity of a system and the characteristics of its environment. To put this in the language of complex systems, much of the increase in systems' complexity can be attributed to needs for mechanisms that enable systems to tackle external complexities that result from spatial and temporal variations and uncertainties in the environments. Consequently, the complexity of the system is driven by the complexity of the environment in which it is planned, architected, and operated (Alderson and Doyle 2010). The notion of environment is fairly general and goes beyond the physical context to include factors such as consumers and stakeholders' requirements, various market forces, and policy, budgetary, and regulatory issues that can affect the performance of the system, and to which the system is expected to respond. The increase in external complexity means that the system should be able to respond to a wide range of scenarios, many of which are not entirely known during earlier phases of the system's life cycle. From this perspective, complexity management is a set of mechanisms that keep the system's complexity (internal complexity) at an appropriate level that can respond to an expected level of external complexity, while ensuring that the system stays robust, resilient, and within budget. Deviating from this appropriate level can result in performance degradation, when the system is under-prepared to respond to the environment (under-complexity), or to unnecessary cost and damaging unintended consequences, when the complexity is above the required level (over-complexity).

Complexity Management Through System's Architecture

Architecting is one of the main jobs of system designers. In most cases, they are directly or indirectly managing some form of complexity through systems architecture decisions. In general, systems architecture is "arrangement of the functional elements into physical entities and relationships between them" (Crawley et al. 2004). More formally it has been defined as "the embodiment of concept, and the allocation of physical/informational function (process) to elements of form (objects) and definition of structural interfaces amongst the objects" (Crawley et al. 2015). These authors further consider seven key decision stages for system architects, including decomposing, mapping, specializing, characterizing, connecting, selecting, and planning (Crawley et al. 2015). Amongst these seven tasks, three of them – system decomposition, mapping functions to forms, and connecting forms and functions – can be considered as primary complexity management mechanisms. Through these tasks, systems are clustered into elements of forms, elements of functions are assigned to them, and the topology of interaction and interfaces amongst these entities are decided.

There are different architecture taxonomies in the literature, depending on the precise definition of general concepts such as platforms, modules, networks, and hierarchies. Joel Moses and his co-authors use the notion of *generic* architecture and classify top-down structured methodologies into platform-based (aka layered) and network-based architectures (Moses 2009; Broniatowski and Moses 2016). Within network systems, some structural forms have been shown to be common across different complex systems, with scale-free architecture being the most famous one (Barabási and Albert 1999), although a number of more recent empirical and theoretical work suggest other structures, especially *core-periphery*, to be common in a wide range of engineered systems (see (Baldwin et al. 2014; Rombach et al. 2014) for a number of empirical evidence and (Heydari et al. 2019, 2015) for theoretical models that proves efficiency and stability of core-periphery structures).

Moving from abstract to practical architectural forms, the notion of reference architecture has proven to be an effective complexity management concept, especially in the field of software and enterprise architecture. The concept has more recently entered the literature of engineering system design (Cloutier et al. 2010) and its literature is rapidly growing. Reference architecture is defined as a set of predefined patterns, template solutions, and common vocabulary for use in business and technical contexts (Clements et al. 2003). Reference architecture can be considered as an inductive effort for complexity management with a goal of generalizing a successful solution to be used in a broader range of similar systems.

In what continues, we will discuss two effective architectural constructs: modularity, as a well-established notion with a long history of academic research, and multi-sided platforms, a more recent construct that has been instrumental in emergence of many modern systems and industries.

Modularity

Different architecture classes have been studied extensively under the general concept of systems modularity in a literature that is at the intersection of engineering design and management sciences (Baldwin and Clark 2000; Ethiraj and Levinthal 2004; Huang and Kusiak 1998; Schilling 2000; Mikkola and Gassmann 2003; Hölttä et al. 2005). Under this general treatment, modularity refers to “a general set of principles that help with managing complexity through breaking up a complex system into discrete pieces, which can then communicate with one another only through standardized interfaces” (Langlois 2002). Modularity has been shown to increase product and organizational variety (Ulrich 1994), the rate of technological and social innovation (Ethiraj and Levinthal 2004), market dominance through interface capture (Moore et al. 1999), and cooperation and trust in networked systems (Gianetto and Heydari 2015) and to reduce cost through reuse (Brusoni et al. 2007).

Modularity as a universal complex management mechanism was first pointed out by Herbert Simon in his classic 1962 paper (Simon 1962), in which a complex system was regarded as one made up of a large number of distinct parts that interact in a non-trivial way. One way to reduce this complexity, Simon suggested, is to decrease the number of distinct parts by encapsulating some of them into modules, where the internal information of each module is hidden from other modules. He argued that this process enables many natural systems to respond effectively to external changes without disrupting the system as whole. More recently, modular structures have been reported in different biological systems such as protein-protein networks, neural cells, and gene regulation networks (Lorenz et al. 2011; Clune et al. 2013; Hansen 2003).

If we consider modularity as a non-binary, complexity management mechanism, the law of requisite variety suggests that for each system, there is an appropriate level of modularity, depending on the complexity of the environment in which the system is operating. Authors in (Heydari et al. 2016) proposed a spectrum that classifies different tiers of modularity into five stages, including Integral, Decomposable, Modular, Distributed, and Dynamic Adaptive (Fig. 2). This framework unifies the engineering notion of modularity (Huang and Kusiak 1998), with network science notion of modularity (Newman 2006). To model the complexity level of the environment, the authors introduced the notion of *space-time complexity* into the framework, which includes the heterogeneity of stakeholders requirements and temporal variations and uncertainties, and used it as an input to four modularity transition operations (M+ operations) that calculates the value of moving from each modularity state to the subsequent one. This framework has been used in systems architecture applications for modular reconfigurable robots (Romanov et al. 2020) and fractionated satellite systems (Mosleh et al. 2016b).

Multi-Sided Platforms

Platform is another term with different meanings, depending on the context and the discipline in which it is used. System designers have long been familiar with a particular notion of platform that is commonly used in the context of new product development. There, the goal of using platforms is to create architectures that can facilitate incremental innovation around reusable components and build a family of related – and often customizable – products. This usage of the term platform is closely related to the concept of modularity and is sometimes referred to as *Internal Platform* (Gawer 2014). In this perspective, platforms are regarded as the collection of assets – components, processes, knowledge, people, and relationships – that a set of products share (Robertson and Ulrich 1998). In addition to the benefits we described for modularity earlier, platforms can save fixed costs, increase efficiency gains in product development, and add flexibility in the system design process. Supply-chain platforms – where a set of firms follow specific guidelines to supply intermediate products or components – are also considered as special forms of internal platforms.

Despite the ubiquity of internal platforms in different engineering systems in the last century, it is the notion of multi-sided platforms (aka *external platforms*) that have become the dominant form of most socio-technical engineering systems and has created complex ecosystems of various stakeholders – consumers, workers, complementors, and regulators. Such platforms are the underlying architecture for crucial products of large technology companies such as Google, Amazon, Apple, and Facebook. They also have resulted in emergence of new forms of products and

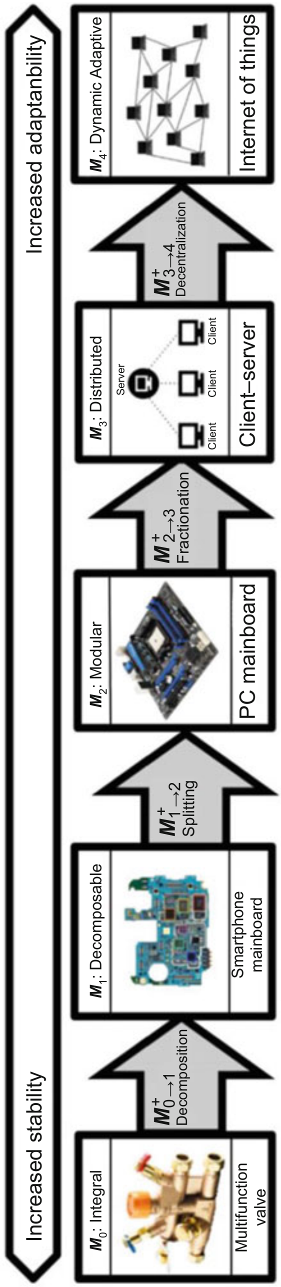

Fig. 2 A five-stage modularity spectrum (see Heydari et al. 2016 for further details)

services, generally known as sharing economy systems. Multi-sided platforms are products, services or technologies that enable complementary innovations through external individuals and firms and facilitate different forms of transactions amongst such entities.

Multi-sided platforms benefit from a large pool of innovation offered by external complementors (e.g., Apple App Market), increased scalability and flexibility (e.g., Airbnb), and sharing scarce resources (e.g., Amazon AWS and Kickstarter). These architectures also balance the level of control and openness through a proper design of platforms core and peripheries. All these benefits are also crucial in the design of most engineering systems. Moreover, given the high complexity of multi-sided platforms – resulted by their high interconnectedness and multi-agent nature – the literature of these systems has focused on many complexity management techniques to decide on the degree of openness for platforms (Heydari et al. 2016; Parker and Van Alstyne 2018), balance competition and collaboration amongst complementors (Gawer and Cusumano 2002), and govern the behaviour of agents on different sides of the platforms and guide their interactions with each other (Tiwana 2013; Tiwana et al. 2010). Models of system governance have also been a centre of attention in the literature of multi-sided platforms where the goal is to specify the decision rights, control mechanisms, and borders between proprietary and shared resources (Gorwa 2019; Tiwana et al. 2010). Given these potentials, system designers can benefit from the existing literature in multi-sided platforms. They can also advance that literature by adapting some of the existing concepts from the platform literature to a wider range of engineering systems.

Complexity Management Through Governance

Approaches to Engineering Systems Governance

Different aspects of governance of socio-technical engineering systems have been studied in different fields and sometimes under different terminologies. The literature is particularly richer in infrastructure systems, especially in smart cities (Meijer and Bolívar 2016; Ruhlandt 2018), distributed energy systems (Burke and Stephens 2017; Koirala et al. 2016; Ehsanfar and Heydari 2016; Goldthau 2014), transportation (Marsden and Reardon 2017; Brooks and Cullinane 2006), and healthcare systems (Rouse 2008). Models of system governance have also been a centre of attention in the literature of multi-sided platforms where the goal is to specify the decision rights, control mechanisms, and borders between proprietary and shared resources (Gorwa 2019; Tiwana et al. 2010).

The growing body of literature concerned with designing large-scale socio-technical systems, typically adopts theories from institutional economics, particularly transaction cost economics (Williamson 1979) and common pool resource management (Ostrom 1990), into the design of the governance structure of engineering systems. Key to this approach (de Wildt et al. 2020; Koirala et al. 2018) is that the engineering system and its governance structures are designed in an integrated fashion, instead of consecutively. Agents in the system and its environment, real or artificial, are equipped with rules and incentives, in a dynamic fashion, to either study appropriate incentive schemes in its design phase or to ensure proper governance of the complex systems once it is operational.

It is worth noting a key difference between the governance of complex engineering systems with the more familiar, well-studied topic of governance in social and economics sciences where foundations of multi-agent systems were first developed. In such systems, much of the role of governance is summarized in designing either appropriate incentives at the agent level, or appropriate rules of interactions amongst agents through which the *designer*'s intended aggregate outcome will be achieved. This last item is the primary focus of *mechanism design*. However, we show in the remainder of this section that such disassociated approach to designing the governance structure, separate from the system itself, is not necessary and that a strong link can be forged between governance and complexity.

Governance of Multi-agent Socio-technical Systems

The link between governance and complexity has been discussed in the past (Duit and Galaz 2008; Keating et al. 2014; Coutard 2002). Although there is a lot to learn from the literature of governance in social and economics sciences, there are some unique features related to governance of engineering systems that require development of new conceptual frameworks and operational methods. First, multi-agent socio-technical systems require a governance scheme that incorporates incentive-based mechanisms (discussed in the literature of mechanism design) and architecture-based mechanisms (systems modular architecture, network structure, and levels of hierarchy). Moreover, designers of engineering systems often have some flexibility in dynamically adjusting the degree of autonomy for systems' constituents, something that is generally not an option for socio-economic systems. Finally, engineering systems often have access to high frequency dynamic data and can activate different types of feedback to various layers of the system at a much higher pace, compared to most social and economic systems.

Incorporating these factors into a governance scheme for complex engineering systems is an open – and crucial – area of research. Here, we briefly discuss a conceptual framework that helps with understanding and organizing governance of multi-agent complex systems framework. This framework is extensively discussed in (Heydari and Pennock 2018). The first point to consider is that even though we refer to emergence as construction of higher forms from lower interactions, it can be useful to view it as a consequence of a dynamic iteration of multi-layered bottom-up and top-down processes. That is to say that interaction of agents at a lower level (e.g., individual agents) gives rise to structural and functional forms at higher levels (e.g., structure and behavioural norms of groups, teams). Here, we refer to these constructive mechanisms as *feedforward* processes. What is generated from such processes will in turn affect lower levels, where individual agents and lower level system constituents adjust their states, strategies, and decisions, learn from higher-level behavioural patterns, and change local structures by adding or removing connections to other agents. These feedback processes collectively are responsible for a great deal of agents' learning in complex multi-agent systems. These feedforward and feedback processes shape collective behaviour of many multi-layer social and natural systems. Take emergence of norms related to social cooperation in the presence of social dilemma (e.g., Prisoner's dilemma as a common abstract model for social dilemma). Individual agents interact according to their strategies that include unconditional cooperation, competition, or more sophisticated, conditional cooperation such as Tit-for-Tat. The aggregate result of these strategic interactions is global and local cooperative norms (feedforward), which in turn influences individual agents through a variety of learning processes (feedback).

What is described up to this point can be found in most organic multi-agent systems and, although useful from a modelling perspective, does not directly help with governing such systems. To be able to add the proper knobs, we note that in complex engineering systems, feedback and feedforward processes do not always affect other layers directly, but are first combined with other exogenous system parameters as demonstrated conceptually in Fig. 3. In most cases, whether a parameter is endogenous or exogenous depends on the definition of system boundary and is particularly a function of relative rate of changes in those parameters in comparison with other endogenous parameters in the system. These exogenous parameters can be related to engineering of the system (architecture and design parameters), policy and incentive side (e.g., dynamics of prices, ownership structures, risk, and

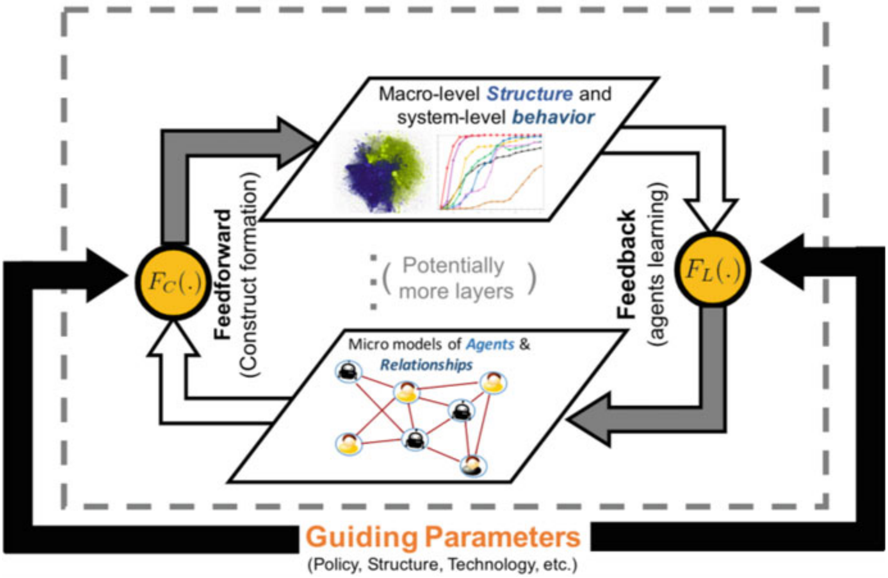

Fig. 3 A high-level scheme of governance for multi-agent socio-technical engineering systems (see (Heydari and Pennock 2018) for more details)

profit disaggregation), or generally the environment of the system with its broad definition that includes physical, policy, technology, and social aspects. The combination of feedforward and feedback processes with exogenous parameters are in general complex and highly non-linear functions, and are noted as $F_C(.)$ and $F_L(.)$ respectively, as shown in Fig. 3. We will briefly discuss approaches to governing engineering systems that include social, policy, or economic incentives within the engineering systems design, in the next section on AI and complexity management.

With this simplified, abstract model of the two-layer system in mind, steering emergence in the model of the socio-technical engineering systems is achieved through (dynamically) choosing appropriate exogenous parameters (those in the environment) that are fed to these two combining functions. Thus, it is not an exercise in varying parameter values to find the optimal policy. The challenge is selecting the basis for exploring variations on the models (Bankes 1993). So, in addition to challenges associated with understanding mechanisms and dynamics of emergence, similar to what the goal of complexity science is, complex systems governance needs to also identify the functions that can successfully incorporate both design and policy parameters.

Given the multi-agent nature of many complex engineering systems, we expect more of such literatures to emerge for designing different governing mechanisms. However, engineering systems also offer *structural parameters* as an additional governance dimension besides incentives. There are mounting evidence that system-level structural characteristics such as communication network topologies and degree of modularity, have significant impact on the behaviour of the system. Although this lens has already been explored in some systems engineering applications, we expect to see this topic, that is, leveraging systems architecture to govern emergent behaviour of complex multi-agent systems, as a growing area of research in the coming years.

Complexity Management and Artificial Intelligence

The discussion on different approaches to complexity would not be complete without commenting on the role of AI. Regardless of whether the current excitement around artificial intelligence are real or will turn out to be another hype in the short term, recent advances in AI, especially in deep reinforcement learning (Mnih et al. 2015), have significant implications for complexity of engineering systems and their management techniques. This is of course not the focus of this book chapter; however, we would like to make a few comments regarding how AI can impact system complexity and complexity management methods, the two streams of discussions we followed in this chapter.

First, we expect inclusion of AI to increase the complexity of systems, primarily through its impact on decentralizing decision-making in the system, the second complexity driver of complexity in this chapter. This is particularly the case for deep reinforcing learning (DRL) agents that enjoy a high degree of learning and adaptability, associated with their use of deep neural networks. Interaction of DRL agents with each other – or with human agents – can increase the number of equilibrium states for complex systems and give rise to new dimensions of emergent behaviour. Moreover, adjusting internal connections amongst systems constituents can be included in the *action set* of DRL agents, which can further increase the complexity due to dynamic changes in the structure of the system.

AI has significant potentials to be used to enhance all the complexity management techniques we discussed in this chapter: In architecture-based methods, they can enable dynamic, evolving architectures by allowing agents to form and remove links to other RL agents, humans, or system modules (Chen et al. 2021). Such dynamic structures are already happening at a lower level during the learning process of deep neural networks – the backbone of most modern RL agents – and the concept can be extended to higher system levels. AI-agents can also play a crucial role in governance-based complexity management methods by steering the collective behaviour of the system through strategic behaviour, strategic link formation, and strategic information sharing. They can also be effective complexity management components in platform-based methods, where they can facilitate and govern the interactions of different sides of the platforms.

In general, studying the behavioural and structural dynamics that result from the collective interaction of rational (DRL) and bounded-rational (human) agents is an active area of research with many open research questions and implications for managing complex socio-technical engineering systems. Such research questions are expected to be amongst crucial parts of research agenda for engineering systems scholars in the next decade.

Final Remarks and Future Directions

Anyone who has attended academic conferences on engineering systems in the last two decades is familiar with the central role of complexity in the themes of those conferences, in keynote talks and panel discussions about the current and future status of engineering systems, and in the topic of many papers and presentations. This is about time to pause, reflect on the achievements of more than two decades of research on complexity in engineering systems and revisit the future goals of this research direction.

We made a case in this chapter for putting more emphasis on identifying and analysing the key *drivers* of complexity – within and outside of systems– as opposed to seeking (near-)universal definitions and quantitative measures. This shift in emphasis gives us a more dynamic perspective, enables us to identify and evaluate system-level trade-offs, and provide us with leverage points that can enable engineering methods to manage system complexity. Moreover, drivers of complexity constitute a smaller set, compared to the commonly used set of common attributes of complex systems, many of which can be deduced from one or a combination of basic drivers. We presented two main drivers: increased interconnectedness amongst systems constituents (network complexity) and multi-level decision-making (multi-agent complexity). These two forces are natural consequences of advances in information and communication technology, and artificial intelligence on the one hand, and changes in the architecture of socio-technical engineering systems that have given rise to open, multi-sided platforms.

In addition to being parsimonious and dynamic, this perspective enables us to form testable hypothesis regarding the relative role of different driving forces that can be later tested using causal identification methods suitable for complex systems. Although there have been some new efforts in this direction in the engineering systems community (Abouk and Heydari 2021; Ke et al. 2021), we expect such empirical investigation of causal drivers of system complexity to become a central focus of research in complex engineering systems in the future, given the importance of such methods in designing policy and governance mechanisms.

We further made a case for engineering system governance and argued that to properly manage complexity, the engineering system and its governance structures need to be designed in an integrated fashion, instead of consecutively. Given the increasing prevalence of platform ecosystems in nearly all aspects of information and resource exchanges in today's world, we expect the governance perspective to become another central theme of research in engineering system, with complexity management as one of its key considerations. We expect these governance schemes to integrate rapid advances in artificial intelligence (AI) and apply these schemes to designing resource allocation rules, communication structures, regulating access rights, assigning liabilities, and aggregating stakeholders' preferences. All these new directions call for a wide range of interdisciplinary research in the coming decade.

Cross-References

▶ Architecting Engineering Systems: Designing Critical Interfaces
▶ Design Perspectives, Theories, and Processes for Engineering Systems Design
▶ Digitalisation of Society
▶ Dynamics and Emergence: Case Examples from Literature
▶ Engineering Systems in Flux: Designing and Evaluating Interventions in Dynamic Systems
▶ Evaluating Engineering Systems Interventions
▶ Formulating Engineering Systems Requirements
▶ Properties of Engineering Systems
▶ Systems Thinking: Practical Insights on Systems-Led Design in Socio-Technical Engineering Systems

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Human Behaviour, Roles, and Processes

9

Petra Badke-Schaub and Harald Schaub

Contents

P. Badke-Schaub
Department of Design, Organisation and Strategy, Delft University of Technology, Delft, Netherlands
e-mail: P.G.Badke-Schaub@tudelft.nl

H. Schaub (✉)
Safety and Security Academy IABG, Otto-Friedrich University, Bamberg, Ottobrunn, Germany
e-mail: Schaub@iabg.de

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Abstract

The development of products, services, and systems can be understood as one integrated effort of addressing psychological, social, technical, and organisational challenges that surround us. Engineering systems design is a human activity aiming at developing highly complex technical products and services. Of course, the challenge for human beings to deal with complexity is not new but the level of complexity has become exponentially higher in the last decades, therefore more complicated, and less manageable. The focus is not only on the user, but also on the designer and different stakeholders (like manager, software systems engineer, mechanical systems engineer, and many more) involved in the system design process. Understanding human behaviour is important to conceive why people make certain decisions and why other people do not make decisions at all. Requirements, needs, and safety are guiding principles for the development process. The process of human-centred development makes it possible to describe the future user groups and activities and thus to develop products and systems that are as close as possible to the (future) needs of the users. The designers can fulfil their tasks in an interdisciplinary exchange with experts from different disciplines.

Keywords

Decision-making · Engineering systems · Human behaviour · Human-centred design · Human factors · Process roles · Workload

Introduction

This chapter focuses on human behaviour, roles, and processes in engineering systems design. Technical development processes are determined by procedures, standards, and legal regulations. In addition to the functionality of the system to be developed, the questions of safety and usability have a determining part. Acknowledging this, the technical standards for engineering systems design play an important role in this chapter. These standards define the framework for the system, and thus the options that the user has. The normative framework (mainly International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC) standards) also connects roles and processes of all stakeholders involved in the project and systems' use.

Due to the inherent complexity of the world, the development of products and services – taking place in various projects – has to be understood as one endeavour of coping with the challenges around us, the psychological, social, technical, and organisational environment (Axelby 1968; Badke-Schaub and Frankenberger 2003; Brusa et al. 2019; Friedman 2003; Vajna 2020).

Engineering systems design is a human activity aiming to develop highly complex technical products and services. Of course, the challenge for human beings to deal with complexity is not new but the level of complexity has become exponentially higher in the last decades, therefore more complicated, and less manageable (Dörner and Schaub 1994; Dörner 1997; Vester 2007).

The foundation of product and system ergonomics is human-system interaction, which is often characterised by the term ‘socio-technical system’ (Trist and Bamforth 1951; Ropohl 2009). The focus is on the tasks to be accomplished within the system. People, organisation, and technology are resources for the fulfilment of the tasks. In many projects, technology dominates the possibilities and limitations of the human user. This dominance is a significant challenge. Technological developments are mainly driven by young male right-handers who enthusiastically develop what they can (Pöppels 2000). However, it is too rarely asked what people need and how they can use it (Pöppels 2000). Norman, the famous creator of the term and concept ‘Human-Centred Design’ goes much further (Norman 2002). He claims that the designer has to think about all technical and non-technical components in a system – and their interrelations – what of course is not possible, because it is unlikely to even know all components of a system and further on to take all components and their interrelations into account – what is simply too much for the human brain.

Depending on the project type, different aspects of the psychological, organisational, and technical perspective can be subsumed under a socio-technical system view. If, for example, the development of a pencil is mainly about material properties and ergonomics, large-scale projects such as designing energy transition, large infrastructure, healthcare services, cyber-technical security, and safety also involve social, political, and security policy aspects.

In anthropometric-physical design (adaptation of the physical conditions of the product (size, shape, forces) to the user), mistakes will be made in the conception and design phase of product and system development (regarding the ergonomic factors of the user, for example, regarding body size, age, sex, or power). In addition, psycho-social and communicative factors such as cognitive processing mechanisms, thinking traps, perception deceptions, expectation breaks, communication problems, emotional and motivational imprints, social processes, etc. will be either insufficient or not at all considered in the conception, design, and project-planning phase. It is often not considered how a ‘normal’ person in a ‘normal’ everyday situation would like to use the product. This leads to products and systems that are difficult to operate, with frictional losses and high error probabilities. This ‘normal’ situation becomes fatal when the user must use the technical system under critical conditions such as stress, hazards, and uncertainty (Badke-Schaub et al. 2011b).

Product and system ergonomics serve different purposes. Within the framework of user experience (UX), it is intended to provide the user with an appropriate support in dealing with the product or system. In addition, the product should also be usable and safe. UX designers are the user-understanders in the development process. They form the interface between the user and the development team. Good products are user-friendly and easy to understand. For the UX designer, the focus is – obviously – on the user experience: How does a user interact with a product? What functions should the product have and how satisfied are users with what kind of service? Satisfied users are loyal users if the product is characterised by intuitive usability, ease of use, and quick learnability. The goal is to inspire users with a product in the long term. UX is also often described with the following statements: UX design is like humour... If you have to explain a joke, it wasn’t good (Norman 2002; Kuang and Fabricant 2019; van de Sand et al. 2020; Yablonski 2020).

To ensure safe operations of the system and to prevent damage to persons directly or indirectly, it is necessary to regularly review occupational safety and the associated laws, guidelines, and regulations. Before commissioning, a product-related risk assessment must be prepared and updated for the system and all planned products, their expected conditions of use, and the reasonably foreseeable misapplications. With the commissioning of the system (whether only partially or in the form of a demonstrator), a risk assessment must be carried out in relation to the workplace, activity, or occupation by determining the work processes and activities (Oehmen et al. 2014).

This concerns questions of occupational health and safety with the essential tasks of preparing risk assessments, ensuring the operational safety of the system and the product safety of the products used, as well as providing appropriate instruction and training. The commissioning phase is critical from an occupational health and safety perspective. Here, based on the product-related risk assessments, the workplace or work process-related risk assessments must be verified. A central element of ergonomic design and occupational safety is risk assessment (and the measures derived from it). A product-related risk assessment must be prepared and updated for the system and all planned products and their use, accompanying the course of the project (Bahr 2014; Ostrom and Wilhelmsen 2019).

In the following sections, aspects of human behaviour, relevant processes, and different roles are discussed as far as they are significant in the context of engineering systems design. Questions of human strengths and weaknesses as well as relevant formal and informal roles are deliberated. These aspects are integrated into processes and rules.

Human Behaviour

Understanding Human Behaviour

Human behaviour is the underlying theoretical concept, which is used to understand and to explain human activities responding to external and internal stimuli (Hutchison 2018). Understanding human behaviour is important to gain knowledge why people make certain decisions and why other people fail to come up with decisions at all (Duffy 1997; Leech 2017).

Design research as a science aims to investigate different facets of human behaviour such as human decision-making, planning, and team processes to understand, support, and improve parts of the design process (Cross et al. 1992). There are manifold criteria to evaluate human behaviour processes. Improvements may result in speeding up processes, reducing human errors or to come up with quicker and more creative solutions for the problem at hand. Of course, the better the understanding of human behaviour, the more specific can be the support for designers, engineers, architects, teachers, etc. It is still a research topic for the next years how to comprehend people, disciplines, and organisations, interpret, and adapt to their various environments (Cross et al. 1997; Birkhofer 2011; Salvendy 2012).

Human behaviour processes have been investigated in different disciplines, such as industrial design, engineering design, engineering systems design, etc. Engineering systems design is one approach building on theories explaining decision making which itself comprehends cognitive and motivational processes (Kahneman et al. 1982). For example, we know that human beings are using two opposing thinking styles, – already introduced by Guilford (1968) – convergent and divergent thinking. In engineering systems design these two processes serve different purposes. Convergent processes are related to analyses and evaluation. Those processes are dealing with framing and integration. The divergent processes play a role in the management of innovation and change. Guilford's concepts were further developed and brought up the famous distinction between slow (more formal) and fast (more intuitive) thinking (Kahneman 2011).

The complexity of real-world problems is characterised by a huge number of interrelated variables. Due to the manifold interrelationships of relevant variables and their mutual influence, medium-term and especially long-term developments are often not adequately considered by problem solvers, decision makers and designers. This can lead to the so-called butterfly effect. The butterfly effect is a phenomenon of non-linear dynamics in complex systems. It occurs in complex systems and manifests itself in the fact that it is not possible to predict how arbitrarily small changes in the initial conditions of the system will affect the development of the system in the long term (Lorenz 1963). Especially situations with ill-defined goals and ambiguous information should be carefully considered, because these situations require often different approaches to the design process and to decision-making processes (Dörner and Schaub 1994). For example, a special focus on problem framing (Dorst 2015) is being recommended before quick actions relying on well-known decisions from the past.

Typically, two basic types of behaviour are distinguished, which are responsible for quick information processes and furthermore explain why increased experience may lead to quick responses but not necessarily to creative answers (Reason 1991). 'Frequency gambling' describes this phenomenon that if a particular course of action has been successful in the past, the person will expect to succeed the next time with the same response – although the situation might be slightly different. This behaviour pattern reduces complexity and guaranties a quick response to the situation at hand, but often small differences are important. Thus, the organisation might not be prepared for new developments and sudden changes (Reason 2013).

The other core mechanism of human behaviour is called 'pattern matching' or 'similarity matching'. In each situation, human perception is looking for relevant information. If enough information is detected to identify a situation, the psychological system is unconsciously searching for a stored scheme to react. Pattern matching helps to react fast and correct to already known situations. It is a kind of an internal procedure or habit (Zimbardo et al. 2013) that also guarantees a quick reaction to new situations by adapting them to fit into the existing patterns.

Figure 1 describes designing as input-process-output model, which is embedded in a social and organisational context. The definition of tasks and roles is manifested in human behaviour and relates to two main different groups of interest.

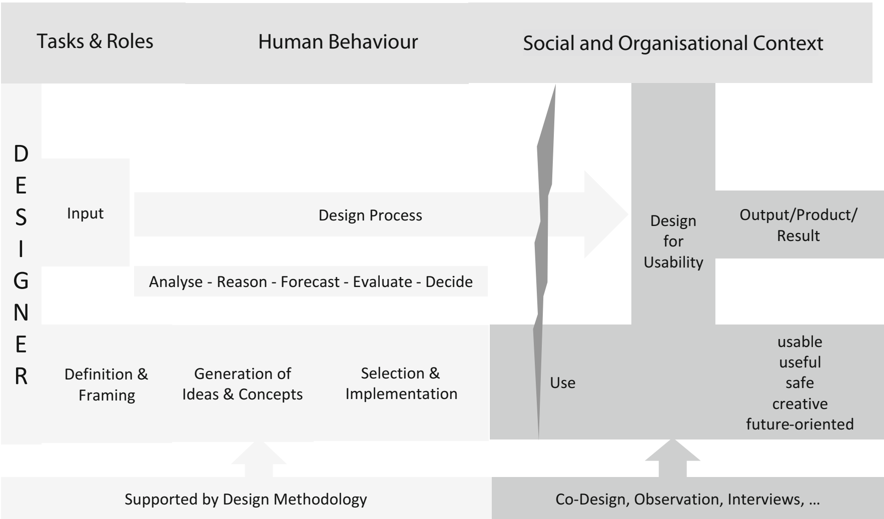

Fig. 1 Descriptive model of the processes playing a role for engineering systems design

The designer on the one side is partly separated from the user, because both groups develop own mental models, and thus the designers' mental model is different from the user's mental model. The designer can only satisfy the needs of the user and other stakeholders when they adapt their mental model by searching information about the content and structure of the user's mental model (Schaub 2007; Young 2008).

The design process can be structured in different ways. In Fig. 1, the main influencing factors are brought into a chronological and content-related dependency. Within the design process, the designers, their behaviour, their abilities, and their expectations play a decisive role. They are involved in processes of usage analysis, assessment, and prediction about usage (and predictable misuse) up to design decisions and evaluation. The approaches, tools and possibilities of design methodology significantly support these processes (Lindemann 2003).

The goal is to achieve the best possible usability for the products and services to be developed. Here, the focus is on close communication, coordination, collaboration, and observation of the user and the (future) use of the product. In particular, the joint development of products and services by designers and users is likely to minimise future problems in usability, misuse, or abuse (European Parliament and of the Council 2006).

An early analysis of which tasks and roles need to be considered in the design process should be carried out at the beginning of the design process. Expectations of capabilities and failures on the part of designers and on the part of users base on what is known about human behaviour (Badke-Schaub et al. 2011b; Dörner 1997; Dörner and Schaub 1994). Finally, this should be examined in the light of the particular social and organisational context. Figure 1 provides a summary of these factors.

Without special emphasis on the needs, possibilities, and constraints of future users, without an appropriate model of the user, designers cannot create successful products and systems (van Veen et al. 2019). Furthermore, the phases of the design process (and the cognitive operations, which are needed to arrive at the result or the final product) are shown in Fig. 1.

Even if this strategy of reducing complexity right from the beginning seems to be an inherent goal for each project, it might occur too early in the process. Driven by the experience of similar situations and ignorance of relevant information makes both the design process and the resulting product, flawed. Reason (2013) – one of the most well-known researchers on human errors – tries to explain why which kind of errors occur. Understanding the process and reasoning patterns that lead to a decision/reaction help to prevent errors.

The design of a product, in addition to compliance with occupational health and safety regulations – especially for work equipment and workplaces – primarily involves more than ergonomic issues (Tillman et al. 2016). Thus, in risk assessment (Oehmen et al. 2014), the products must also be evaluated within the framework of the regular and expected work processes in regarding to risks to the health of the person working there. To ensure the lowest possible risk or the best possible design of the work equipment, it is important to provide a working environment that is sensibly designed regarding use and tasks in a human-compatible design (Konz 2017).

The aim of ergonomics is to optimise the holistically considered work system consisting of people, organisation, and technology. In general, the aim is to reduce the workload of people, to avoid physical and psychological (consequential) damage and to increase work performance.

In the ergonomic design of products, workplaces, and systems, it is therefore essential to consider all interfaces between human and work system. This includes the technology used, the processes and the organisation of work. In addition to the anthropometric-physical design of workplaces, this also includes, for example, ensuring good usability of the software used and providing environmental conditions that promote concentration and attention (Schlick et al. 2010).

Usability according to ISO 9241 means the extent to which a product or system can be used for effective, efficient, and satisfactory processing of the intended tasks. Both the user groups and the application context must be defined (ISO 2019).

The term User Experience (UX) has been coined by Norman (Norman 2021). According to him UX includes all cognitive and emotional perspectives and impressions of a user during the interaction between the user and the product or system. An important aspect of the UX view is the question of how the product or system fulfils the user's expectations (Travis 2019). ISO 9241 describes user experience as the behaviour of a user that results from interaction with the product or system. This includes the emotions of the user, his psychological, and physiological reactions, expectations, and behaviour.

Human Factors, sometimes referred to as human influencing variables, are used to summarise the psychological, cognitive, and social factors that influence human-product/system interactions in socio-technical systems. Human Factors focus on the physical, anthropometric, and cognitive characteristics of human beings (Badke-Schaub et al. 2011b; Tillman et al. 2016). Human behaviour is not analysed per se, but it is part of socio-technical systems, which consist of psychological and social, of technical, of procedural, and finally of organisational factors.

Engineering systems are regulated by many laws, standards, ordinances, and regulations. Among other things, the focus is on the chemical or biological substances used and produced, the technology, the environment, but also the organisation and the employees.

If one sees engineering systems in the triangle of human-organisation-technology, human is revealed as a central aspect in regard to several respects: as part of the interaction organisation-human and technology-human and also as the one who conceives, constructs, manufactures, operates, and checks technology and organisation.

The methodological and scientific background to all aspects of human action in the professional and operational environment is the Human Factors approach, which brings together the findings and expertise from many disciplines to develop and implement resilient, practice-relevant solutions for modern, socio-technical systems, and issues. In recent decades, Human Factors have been increasingly recognised as a safety-critical factor in various industries. In addition to the aspects of technology and systems, the so-called technical and non-technical skills of operators have become the focus of attention.

While technical skills primarily refer to the abilities, skills and knowledge that are necessary (but not sufficient) to manage and control the technical system (e.g., control room operation, starting an aircraft), non-technical skills include those psycho-social abilities, skills and knowledge that describe how to deal with one's own working ability, as well as with the respective teams and crews (e.g., dealing with stress).

Human-system interaction is understood to include both, in the sense of the human-machine interface, ergonomic aspects of operating machines, equipment or systems in general, in the sense of mechanical or physiological parameters (e.g., brightness, distances), and, building on this, all aspects that play a role in the interaction with the system and the work task (expectations, cognitions, motivations, social aspects). These topics taken together are summarised under the keyword human-system integration.

It is necessary to identify which aspects from the areas of human-machine interface, human-system integration and human factors have occurred in the past (or are suspected to occur) as problems in the operation of systems or are to be expected in the future.

The focus on human behaviour in engineering systems design is, in the context of the work process, the investigation of the perception, communication and information processing processes, as well as the operating and decision-making processes of the operators in the plant, as well as of the management and the organisation. Through cognitive work analyses or in-depth stress/strain investigations, technical, social, and psychological conditions for inefficiencies and faulty conclusions or actions are identified (Design-Society et al. 2019).

Conversely, possibilities of stress regulation to cope with stressful situational conditions, possibilities of improvement for attention and vigilance as well as the restoration of operational capability for certain tasks are worked out.

Furthermore, the development and maintenance of individual situation awareness (SA) and understanding of the current situation between the operators themselves and with management (team situation awareness) are recorded as performance-determining factors in the coordination of work. Adequate situation awareness is based on relevant and valid information, enables efficient coordination and is the basis for planning further action or briefing the team in critical situations.

Some typical phenomena are listed here as examples for explanation:

- Simple errors in the process sequence or work process, such as right-left confusion, colour confusion, number confusion, etc.
- More complex errors in the process flow or work process, such as incorrect expectations regarding the system behaviour in the event of a malfunction, incorrect assumptions about the process or system status; incorrect application of procedural rules, standard operating procedures (SOP), etc.
- Errors in coordination, e.g., unclear communication, no common picture of the situation, diffusion of responsibility, leadership problems, etc.

Workload and Mental Stress

Many factors in human-system interaction play a role in engineering systems design. The central position is taken by workload. It is critical for the question of individual requirements, for the necessary technical support, for possible errors (during development and in use) and for job satisfaction. Both too high and too low workload can have negative effects. Therefore, knowledge of the factors influencing workload is important for an appropriate and sustainable engineering systems design.

The ergonomic design of products and systems has as an essential goal to control the load and stress ("workload") during product or system use (Gawron 2019). The term strain subsumes all external influencing factors, which can trigger a reaction of the organism. Stress is understood to mean any reaction caused by an external influencing factor. This can affect the entire body, an organ system, a single body organ or an isolated function of an organ. Nevertheless, stress on the human body and the human mind must be seen as a reaction of the whole body and always as a consequence of stress from all areas of life (Jex 1998).

The exposure at a specific product, system, or workplace can be

- From the nature and difficulty of the work task itself.
- From the physical, chemical, biological working environment conditions.
- From the specific enforcement conditions (e.g., technical aids, time limits).
- From social relationships with superiors, employees, and other peoples.

and lead to stress which is

- Non-specific (e.g., in the sense of a general activation with each activity, recognisable by an acceleration of heart and respiratory rate, increase in the degree of alertness).
- Specific (e.g., sweat secretion under the influence of heat, activation of certain enzyme systems when exposed to pollutants, special adaptation mechanisms when similar stresses are repeated).

Mental strain (as objective input) and stress (as an individual result) are defined in ISO 10075. The concept of mental stress is based on the occupational psychological stress and strain concept and includes all (objective) factors acting on the person from outside which require the worker to be involved. Thus, stress results from the requirements of the respective work activity and can lead to physiological and psychological workload. This results in changes of the performance, well-being, and health of the working person (ISO 2017).

The objective of a workload analysis is the investigation of the perception, communication, and information processes as well as the operating and decision-making processes of the users when operating a system. The load/stress analysis (or workload analysis) identifies technical, social, and psychological conditions for inefficiencies and wrong conclusions/actions. Conversely, possibilities of stress regulation for coping with stressful situation conditions, improvement possibilities for attention and vigilance and the restoration of the ability to use the system for certain tasks are worked out.

From the perspective of a workload analysis, not only the classic end user is object (or subject) of strain and stress. The designer, in his or her working environment, with his or her tools and processes, can and must also be considered and supported regarding an adequate degree of workload. Workload analysis examines the performance of individual persons, teams, and crews under various requirement conditions. The performance is evaluated according to the understanding of the situation, the tactical performance and the subjective and objective experience of stress and psychological strain. On the other hand, the competence requirements of the core persons are assessed (Ganster and Rosen 2013).

Mental stress is also dependent on personal characteristics, qualification and current performance and may have promoting (positive) or adverse (negative) effects (Fig. 2).

To systematically determine potential stress factors of a work activity, it is necessary to consider which aspects of a work activity have an influence on human behaviour. These are three main areas:

- Working activity
- Environmental conditions
- Organisational conditions

The work activity itself influences not only the quantity and quality of the work results through its content, i.e., through the main work task and its associated partial and secondary activities, but also the strain and possible errors of the operator.

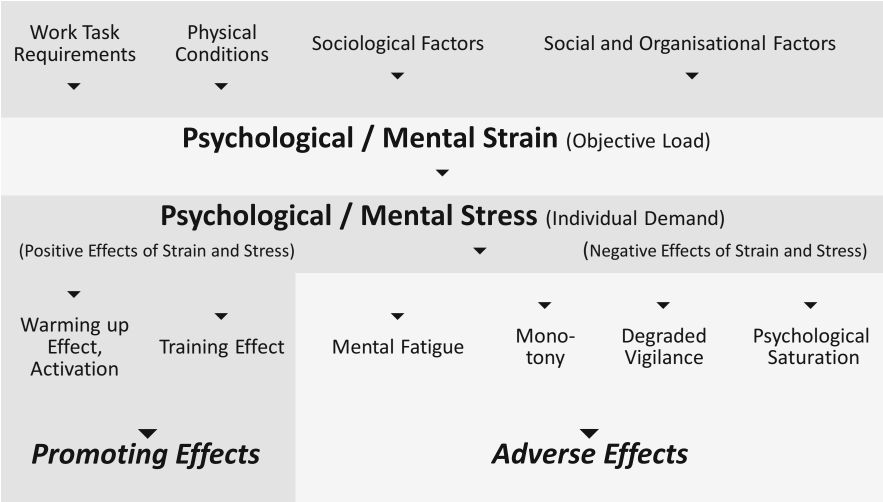

Fig. 2 Context and genesis of mental stress and strain as aspects of workload

For example, more varied activities can prevent early fatigue caused by monotony. The responsibility assigned to an operator/guide with a task can have a beneficial effect on the one hand, but also a dysfunctional one on the other. When it comes to stress, for example, requirements for the design of the workplace and work activities are formulated in 'ergonomics of human-system interaction' ISO 9241 (2019), 'user-oriented design of interactive systems' ISO 13407 (ISO 1999b), in 'system safety' MIL-STD-882 (Departement of Defense 2012), among others.

The environmental conditions in which a work activity is embedded include the design of the workplace. A dysfunctional designed workplace represents a stress factor that can have a dysfunctional effect not only on the strain on the operator, but above all on the quality of work (incorrect work results).

Organisational conditions include potential stress factors that do not result from the work activity itself, but from its framework conditions. For example, an inadequate shift or pause system can lead to states of exhaustion among operators.

Stress factors that are actual present in a workplace do not necessarily lead to dysfunctional behaviour. The extent to which determined stress factors causes dysfunctional stress depends on several factors:

- The strain itself (type of stress, intensity, importance within the work activity, duration, and frequency of occurrence).
- The design of the framework conditions of the work activity.
- Characteristics, abilities and skills of the operator or the typical characteristics of the role/job description.

A workload analysis is used to determine the characteristics of product and system usage, work activity, work environment, work organisation and special requirements. These characteristics are either recorded explicitly or can implicitly influence the recording and evaluation of the workload. It can be recorded as various aspects, each with the appropriate (objective and/or subjective) methods (Schaub 2020).

The collection of the characteristics is embedded as an analysis phase in the general procedure of a workload analysis. Only if the objectives and scenarios to be considered are clarified, if the questions/hypotheses are appropriate, and if the evaluations are methodologically sound and pragmatically oriented, reliable, and useful results can be expected.

With the automation of a multitude of processes, there are new requirements and burdens for users, but also for designers.

Themes like the relation between work activity and human error have been discussed in many different disciplines. One of the most famous propositions are the so-called ironies of automation by Bainbridge (1983). Bainbridge, see Table 1, focus on the distribution of tasks and requirements between user and automated system. According to Bainbridge, the focus is on the current possibilities of the technology and not on the capabilities and limitations of the human user.

These findings result in certain essential tasks for engineers in the development of an adequate human-technology interaction:

- State information must be provided intuitively.
- Appropriate situation awareness must always be supported.

The role of the operator in automated systems must therefore be planned, it must be defined what the automation should do, how this should be communicated to the automation. It must be ensured that the execution can be monitored, and that the user can intervene if the automation does not implement the given directives as expected. There should be opportunities for users and systems to learn from experience and to build an appropriate mental model of the automated environment (Lindemann 2003; Badke-Schaub et al. 2011a).

In this section some aspects have been presented that constitute multiple behaviour and can play a role in the context of the system design. The focus is not only on

Table 1 Ironies of automation (Bainbridge 1983)

Designers see human beings as an essential source of error and therefore human beings should be replaced; but designers are also human beings; operational errors are often design errors
High complex, therefore, not automatable tasks are transferred to humans; what of course is the weakest link in the process chain
Humans are replaced by automation, because these systems are more efficient; however, humans should continue to monitor, check, correct errors and, if necessary, take over the machine manually
The most reliable automation systems require the most elaborate user training as the user cannot learn the system by training off the job but should still intervene in critical situations. Unreliable systems require little training, as the user continuously controls the system and thus knows the strengths and weaknesses of the system

the user, but also on the designer and all stakeholders involved in the system design process. Understanding human behaviour is important to understand why people make certain decisions and why other people make different decisions or do not make decisions at all (Duffy 1997; Leech 2017).

Example: Human Behaviour and the Human-Robot Collaboration

We want to use the example of collaboration between humans and robots to illustrate the importance of considering human behaviour in engineering systems design.

With the so-called robot laws, the science fiction author Isaac Asimov describes in his story Runaround (Asimov 1950) the basic rules of cooperation between humans and robots on a behavioural level: A robot must not harm a human being or allow harm to be done to a human being through inaction. A robot must obey commands given to it by a human being – unless such a command would conflict with rule one. A robot must protect its existence, if this protection does not conflict with rule one or two.

Asimov has written many stories about these rules and especially about their technical and philosophical implications; his story 'I, the Robot' (Asimov 1950) is very well known; in the field of real existing robots, these rules are – still – dreams of the future, as they require considerable cognitive abilities that are not yet feasible.

Human-Robot Collaboration (HRC) systems serve, for example, as lifting or positioning aids for loads in production. The automotive manufacturer AUDI, for example, uses an HRC system on the production line in the automotive final assembly in Ingolstadt, Germany, which hands components to the production worker in an ergonomically favourable position. In addition to improving ergonomics and health protection for the employees, HRC systems can improve process safety and, in particular, productivity. It is important that the behaviour of the human as well as the behaviour of the robot is analysed, understood, and appropriately considered in the design.

Processes for Human-Centred Product and System Design

There are multitudes of tasks that a designer must consider. To ensure appropriate, effective, and efficient processes for human-centred product and system design, a delimitation of the ergonomic aspects to be considered should be carried out. The future user groups and activities must be described in more detail. This could be based on available documents, findings from testing of earlier versions, demonstrators, and explanations from the various workshops with users and other exchanges of information.

The following list shows relevant examples of reference documents for the design of work centres:

- Handbook of Ergonomics (Bullinger et al. 2013)
- ISO 9241 Ergonomics of human-system interaction (ISO 2019)
- MIL-STD-1472G Human Engineering (for military products) (Departement of Defense 2012)

Specific ergonomic analyses can be supported by CAD systems for human-system ergonomics (e.g., the software RAMSIS (FAT 1995)). Typical results of these analyses are questions concerning:

- The perceptibility of information (visual analyses)
- The accessibility and operability of devices and control elements
- The necessary adjustability and customisability of the products (for example, in the case of an office workplace, the adjustability of chairs and tables)

Ergonomic concepts should be developed under the condition that they meet the requirements of the respective laws, regulations, and state of the art (and science, if applicable). The state of the art (in technology) at the time of placing on the market shall be applied. A product is not defective simply because an improved product with a higher safety standard comes into the market later. Beyond this, liability applies in cases of product observation defects. Any conflicts arising about the fulfilment of the requirements must be recorded and resolved with the client and the designers.

Analysis of Ergonomic Recommendations

This section explains ergonomic aspects and recommendations that can be applied in the ergonomic analysis. The intended user group and their expected use of the product or the system must be defined. But also expected misuse and abuse of the product should be analysed (European Parliament and of the Council 2006). Subsequently, the generic activities that are necessary to fulfil future usage scenarios should be described (Guastello 2013; Kan and Gero 2017; Stuster 2019).

The user group to be considered can be classified according to different criteria such as age, gender, body measurement. For example, typical legal requirements for office workplaces are the consideration of the size range from the lower 5th percentile, female, to the upper 95th percentile, male; here, the respective reference year of the statistics used must be considered (Panero and Zelnik 1979).

Excessive strain on users with or at a product can be avoided by a safe and ergonomic design with regard to the use of work equipment (in the case of office workplaces, for example, worktables, office chairs, monitors, etc.). A properly designed product/system also ensures that users can work without health problems or reduced performance. This is of great importance, for example, when monitoring activities to ensure a high level of concentration and attention of the operators.

In the case of office workplaces, ergonomic considerations about lighting, room climate and noise protection are important. Here, the recommendations of the Handbook of Ergonomics (Bullinger et al. 2013) and ISO 11064 (ISO 1999a) can

Table 2 Requirements for office workplaces regarding lighting can be identified (ISO 1999)

Natural light is always preferable to artificial light
Screens should be placed at a 90° angle to the window
Matt screen surfaces should be used to avoid reflected glare
Artificial lighting should be provided by a combination of direct and indirect lighting
Too small differences in luminance between the workplace and its surroundings should be avoided. The required reflection and gloss levels of the work equipment and environment are maintained

be referred to. It must be taken into account that the evaluation of the relevant requirements should be adapted to the respective time and progress of product or system development.

For example, the requirements in Table 2 for office workplaces regarding lighting can be identified (ISO 1999).

Ergonomic Specifications During Development – Design Recommendations

Beyond the physiological factors of product ergonomics, design recommendations are formulated for the cognitive factors of ergonomics. This is covered by the ISO 9241 standard, which relates to interaction with products and systems. Originally, it was formulated regarding the dialogue design of software, but today it is applied to practically all interactive systems.

The standard ISO 9241 (ISO 2019) formulates seven guiding ideas, which are relevant for the design of a human-system (product, machine, system) interface (see Table 3).

Empirically the current attention, stress and personal preferences interacting with a device or system can be recorded using various methods (describe, e.g., in: ISO 10075 (ISO 2017) and ISO 6385 (ISO 2016)).

To be able to realistically assess ergonomic requirements and effects, it is necessary to survey the physical (fatigue, weight, etc.) and psychological factors (attention, stress, strain, etc.) in interaction with the product, the system or at the workplace in the form of ergonomic task and process analyses. These analyses should be carried out for the different user roles and for different usage scenarios. Specific framework conditions such as use in private or professional environments, levels of automation of the systems or different shift should be considered. To be able to assess and record the ergonomic implications, the task, workload, and stress analyses should ideally be carried out directly during the product or system use, for example at the workplace with realistic, practical tasks. The ergonomically relevant factors are recorded by technical recording methods, in particular by so-called eye-tracking. The use of eye-tracking measurements offers a high measurement quality and a good resilience of the results (Bergstrom and Schall 2014; Duchowski 2017).

Table 3 ISO 9241 (ISO 2019) Guidelines for human-system products

Task Adequacy: An interactive system is task adequate when it supports the user in completing his work task, i.e., if functionality and dialogues are based on the characteristics of the work task rather than on the technology used to complete the task
Self-descriptiveness: A dialogue is self-descriptive to the extent that it is always obvious to the user in which dialogue, at which point in the dialogue he or she is, what actions can be taken and how these can be carried out
Conformity with expectations: A dialogue is in conformity with expectations if it corresponds to the user concerns foreseeable from the context of use as well as generally accepted conventions
Learning facilitation: A dialogue is learning facilitating when it supports and guides the user in learning how to use the interactive system
Controllability: A dialogue is controllable if the user can start the dialogue flow and influence its direction and speed until the goal is reached
Error tolerance: A dialogue is error-tolerant if the intended work result can be achieved with either no or minimal correction effort on the part of the user despite recognisably incorrect entries
Suitability for individualisation: A dialogue is individualisable when users can change the human-system interaction and the presentation of information to adapt it to their individual abilities and needs

The knowledge gained in this way is verified and expanded through observations by experts, through interviews with users, but also with trainers and other persons if necessary, and – if available – through analysis of documents of existing work processes (including job description, job specification, job planning, training and employee qualifications, safety-relevant regulations, checklists, etc.).

Since not all situations can be researched in an empirical setting (for example, because the product does not yet exist or the application situation is dangerous or can only be produced at great expense), the method of the so-called Cognitive Walkthrough lends itself. This involves thinking through the respective usage scenario and the associated interaction processes with the product or system. With the Cognitive Walkthrough, ergonomic experts, designers, and users put themselves in the shoes of a hypothetical user and work through the various work steps, stress, strain, and error possibilities. The Cognitive Walkthrough (Hartson and Pyla 2018) is a proven usability/workload inspection method in the context of expert/user/operator surveys in analytical evaluation procedures and is used when empirical evaluation procedures (e.g., analysis directly at the workplace) are not possible to capture the work or human-system interaction process.

In order to identify ergonomic weaknesses in the procedures and given processes, the data and findings resulting from the observations, from the analysis of the documentation and from the workshops and interviews with the users are analysed with the common methods of weak point analysis. For example structured analysis, SWOT analysis (strengths, weaknesses, opportunities, threat), FMEA (failure mode and effects analysis), causal tree method, Ishikawa diagram, root cause analysis, FTA (fault tree analysis), ECFA (events and causal factors analysis), HFIT (Human Factors investigation tool) – to name but a few – are examined (Sarsby 2016; Mikulak 2017; Monat and Gannon 2017; Okes 2019).

Table 4 General principles for interaction design (Molich and Nielsen 1990; Nielsen and Mack 1994)

1. Visibility of the system status: The system should always keep users informed about what is going on, through appropriate feedback within reasonable time
2. Match between system and the real world: The system should speak the users' language, with words, phrases, and concepts familiar to the user, rather than system-oriented terms. Follow real-world conventions, making information appear in a natural and logical order
3. User control and freedom: Users often perform actions by mistake. They need a clearly marked 'emergency exit' to leave the unwanted action without having to go through an extended process. When it is easy for people to back out of a process or undo an action, it fosters a sense of freedom and confidence. Exits allow users to remain in control of the system and avoid being stuck and feeling frustrated
4. Consistency and standards: Users should not have to wonder whether different words, situations, or actions mean the same thing. Follow platform conventions
5. Error prevention: Even better than good error messages is a careful design, which prevents a problem from occurring in the first place. Either eliminate error-prone conditions or check for them and present users with a confirmation option before they commit to the action
6. Recognition rather than recall: Minimise the user's memory load by making objects, actions, and options visible. The user should not have to remember information from one part of the dialogue to another. Instructions for use of the system should be visible or easily retrievable whenever appropriate
7. Flexibility and efficiency of use: Accelerators – unseen by the novice user – may often speed up the interaction for the expert user such that the system can cater to both inexperienced and experienced users. Allow users to tailor frequent actions
8. Aesthetic and minimalist design: Dialogues should not contain information, which is irrelevant or rarely needed. Every extra unit of information in a dialogue competes with the relevant units of information and diminishes their relative visibility
9. The system should help users recognise, diagnose, and recover from errors: Error messages should be expressed in plain language (no codes), precisely indicate the problem, and constructively suggest a solution
10. Help and documentation: Even though it is better if the system can be used without documentation, it may be necessary to provide support and documentation. Any such information should be easy to search, focused on the user's task, list concrete steps to be carried out, and not be too large

An excellent orientation, how to integrate human perception, thinking, and decision making into engineering systems design are the 10 heuristics of Nielsen (Molich and Nielsen 1990; Nielsen and Mack 1994) to general principles for system and interaction design (see Table 4).

The ironies of automation (Table 1) from Bainbridge (1983) and self-critical common sense are worth considering (Frankenberger et al. 1998; Norman 2002).

Occupational Safety and Risk Assessment

Occupational health and safety measures serve to prevent accidents and health hazards at work. A further objective is the humane organisation of work. Manufacturer, distributor, operator, and employer are responsible for occupational health and safety about the product. In addition, the employer must establish a functioning occupational health and safety organisation in the company with the obligation to carry out a risk assessment. For this reason, questions of ergonomics cannot be dealt without simultaneously taking occupational health and safety into account (Friend and Kohn 2018; Goetsch 2018).

Occupational health and safety management systems (OSH management systems) are an effective instrument for supporting and improving occupational health and safety.

According to the Occupational Safety and Health Act (Occupational Safety and Health Administration 1970), the employer is obliged to appoint company doctors and occupational safety specialists according to certain requirements. These have the task of supporting him in occupational health and safety and accident prevention in his company. They are not bound by instructions when applying their expertise and must not be disadvantaged in the performance of their duties.

The Occupational Safety Act is substantiated by the accident prevention regulations of the statutory accident insurance institutions.

Statistics show a high proportion of accidents occurring during the use of workplaces. For example, floors, traffic routes and stairs are named as accident black spots in the first place. To prevent accidents, the ordinance specifies suitable measures or protection targets for the setting up and operation of workplaces, including traffic and escape routes, storage and ancillary rooms, but also sanitary, break/standby and first aid rooms as well as accommodation.

The risk assessment forms the basis for comprehensive occupational health and safety to prevent accidents at work and work-related health hazards. The employer but also the manufacturer (and its designers) must observe various principles (Table 5) in occupational health and safety measures and identify possible limitations of these principles in the course of the risk assessment (Bahr 2014; Ostrom and Wilhelmsen 2019).

To comply with these principles and to avoid the hazards listed below, a risk assessment must be carried out. This can use various methods/procedures (plant

Table 5 Principles in occupational health and safety measures (Bahr 2014; Ostrom and Wilhelmsen 2019)

Any danger to life, physical and mental health must be avoided or minimised as far as possible
Dangers must be tackled at their source. This means that it is better to have a technical solution than an organisational (regulation) or personal (training) one (TOP – principle: Technical, then organisational, and only then personnel solution)
The state of the art, occupational medicine, hygiene, and assured ergonomic findings must be taken as a basis
Technology, work organisation, working conditions, social relations, and the environment must be considered in a meaningful way regarding the product and workplace
Individual protection measures are secondary to other measures
Special risks for particularly vulnerable groups of users and employees must be considered
Appropriate instructions of the users and employees must be ensured
Gender-specific regulations are inadmissible (except for biological ones, which are mandatory)

Table 6 The hazard classes (Ericson 2015)

Mechanical hazards
Controlled moving unprotected parts, parts with dangerous surfaces, transport and mobile work equipment, uncontrolled moving parts, falling/slipping/tripping/buckling, falling
Electrical hazards
Electric shock and arcing, static electricity
Hazardous substances
Lack of hygiene when handling hazardous substances, inhalation of hazardous substances, skin contact with hazardous substances, physical and chemical hazards, e.g., fire and explosion hazards, uncontrolled chemical reactions
Biological agents
Infections, sensitising effects for example aerosol formation
Fire and explosion hazards
Flammable solids/liquids/gases, explosive atmospheres, explosives, and pyrotechnic articles
Thermal hazards
Hot media/surfaces, cold media/surfaces
Hazards due to specific physical agents
Noise, ultrasound / infrasound, whole body vibration, hand-arm vibration, optical radiation, ionising radiation, electromagnetic fields, vacuum / overpressure
Hazards due to working environment conditions
Climate, lighting, suffocation/ drowning, inadequate escape routes, insufficient space for movement at the workplace/ unfavourable workplace layout/ inadequate breaks/ sanitary facilities, man-machine/ computer interface
Physical load/work severity
Lifting/ holding/ carrying, pulling/ pushing, manual work with low physical forces, forced posture forced posture, climbing/ climbing, work with increased exertion and/or force
Psychological factors
Work content / task, work organisation, social relations, working environment
Other hazards:
Violence in the workplace, by animals, by plants/plant products)

inspections, users/employee surveys, safety inspections of work equipment, special event, safety, or risk analyses). The expected risk potential, the work processes and work equipment used, experience and personnel and organisational requirements in the company determine the type and scope of the risk assessment.

The hazard classes in Table 6 must always be considered (Ericson 2015).

Operational and Product Safety

Operational safety is the safety of plant, machinery, equipment and working materials used in commercial operations. The various ordinance on industrial safety and health summarises the occupational safety requirements for the provision of work equipment by the employer and the use of work equipment and systems by users and employees at work, including the operating regulations for systems requiring monitoring (Asfahl and Rieske 2018).

Product safety covers a wide range of legislation relating to the making available of products on the market. The supplier must prove compliance with the relevant directives when using the product (Owen and Mary Davis 2020).

It is important, but certainly not easy, to consider misuse or foreseeable abuse. In terms of content and concept, this corresponds with product liability law. Misuse can occur, for example, out of convenience (rules of use are ignored) or because the operation is not clear enough for the user. Product liability law and various standards requires that misuse must be considered by the manufacturer. Every product sold to end users must therefore be insured against dangerous failure (in the sense of personal injury, death). But neither the standards nor product liability law offer the user protection against intended misuse, i.e., deliberate misapplication (European Parliament and of the Council 2006).

The supplier of products must state whether the equipment offered is covered by at least one CE (French: Conformité Européenne) directive and declaration of conformity (Tricker 2020). By affixing the CE marking, the manufacturer, distributor or EU authorised representative declares, in accordance with European regulations that the product conforms to the applicable requirements laid down in the community harmonisation legislation concerning its affixing.

The CE marking indicates that the product complies with the basic product safety regulations applicable to the product. This represents a guaranteed product property. If it is subsequently established that, for example, a harmonised standard applicable to the product states a protection objective that has not been implemented, this constitutes a defect in the product. In this case, the manufacturer/supplier can be requested to remedy the defect.

During configuration, care should be taken to ensure that the functional interlinking of different installations does not result in a system that would result in an independent conformity assessment procedure. Equipment from different manufacturers is often purchased and used by the users or operators as a standalone system. The result is a chained system, in the parlance of the Machinery Ordinance (European Parliament and of the Council 2006) a 'totality of machines'. As a rule, each manufacturer issues a declaration of conformity for the product or plant supplied. Whether a CE conformity assessment procedure must be carried out for the interlinked system and a declaration of conformity issued depends on the following factors (Carve 2019).

- There must be a functional link.
- There must be a control system link.
- There must be a safety link.

Only when all three of the above conditions are met is it necessary to draw a declaration of conformity for the linked system. In this case, care should be taken to ensure that in the procurement process this task is entrusted to a single contractor.

Hazards can also arise in particular from insufficient qualification, abilities, and skills, as well as insufficient instruction of the users (Reason 1991; Dörner 1997; Ericson 2015).

The employer must instruct the employees in such a way that they are able to recognise health hazards as such and react to them appropriately. A prerequisite for regular instruction is a precise adjustment to the respective work situation in the company.

Instruction and training are a subordinate measure to counteract hazards and is only chosen if the technical or organisational possibilities are exhausted.

It is important to exclude hazards in the order given in Table 7.

To be able to react according to the rule in case of emergencies, safety training shall be defined and conducted regularly (e.g., evacuation, behaviour in emergencies, e.g., in case of fire and the like).

At this point, the effects of automated functions should be pointed out. Contrary to the frequently expressed opinion that automation reduces the need for training and proven competence of operators, the opposite is true for safety-critical systems (Bainbridge 1983). In order to be able to act in case of compromise, failure or malfunction of the system, the operator needs comprehensive training.

The principles in Table 8 must be observed during commissioning.

During commissioning, further sources of danger must be evaluated from the point of view of occupational safety (regarding the requirements of the product safety and within the framework of a risk assessment). This assessment can only be made once the work system has been specifically configured.

This section described various processes that play a role in system design. The main focus was on the perspective of use and the user. The requirements, needs and safety are guiding principles for the development process. The process of human-

Table 7 Sequence to exclude hazards (European Parliament and of the Council 2006)

Avoid/eliminate source of danger.
Safety-related measures to separate the hazard from humans (spatial separation, e.g., encapsulation, extraction, protective grids, light barriers)
Organisational measures to separate the hazard from the person (work organisation, work sequence, working time and break arrangements)
Use of personal protective equipment to prevent/reduce exposure to humans (e.g., gloves, hearing protection, safety shoes, breathing protection)
Behaviour-related measures for safety-oriented behaviour (testing, monitoring, training, and instruction of employees)

Table 8 Safety principles during commissioning

In the case of machines, commissioning may only take place when the machine meets the requirements of the relevant directives and has been verified and documented by the declaration of conformity and CE marking
Hazard assessment must be available with the statement of safe commissioning prior to first commissioning
Risk assessment must be updated during use

Table 9 Basic principles of Human-Robot Collaboration

Safety-related monitored standstill: Robot stops when the employee enters the shared workspace and continues to move when the employee has left the shared workspace again
Manual guidance: Robot movement is actively controlled by the worker using appropriate equipment
Speed and distance monitoring: Contact between the worker and the robot in motion is prevented by the robot
Power and force limitation: The contact forces between employee and robot are technically limited to a harmless level

centred development makes it possible to describe the future user groups and activities and thus to develop products and systems that are as close as possible to the (future) needs of the users.

Example: Operational and Product Safety and the Human-Robot Collaboration

The four basic principles of Human-Robot Collaboration (HRC) are described in the standard DIN EN ISO 10218 'Industrial robots – Safety requirements', see Table 9.

In addition to the technical conditions of the robotic system, the organisational and personnel conditions must be set in terms of safe handling. If an HRC system is to be designed and developed, a checklist of all safety aspects must be worked through on the potential HRC system (and on the future workplace). To this end, future users should also be involved in the design phases of a collaborative system from the beginning. In addition, IT security measures, emergency procedures and automation aspects should be considered. The protective principles of HRC massively limit the possible uses of machines in effective and efficient human-robot collaboration. This means that the benefits of robots, their speed, power, and versatility in a collaborative environment are limited or non-existent. Asimov's Law Number 1 – A robot must not harm a human being or, through inaction, allow harm to come to a human being – obviously allows for more opportunities for a robot's capabilities to flourish. But how can this idea that the robot concretely knows what it should and should not do in the respective situation be implemented? This can surely only be done by using all approaches of artificial intelligence (not only the currently used learning algorithms). This is not only about expanding the cognitive, but also, for example, the empathic abilities of the robot.

Roles in the Context of Human-Centred Product/System Design

As an integral part of every (socio-technical) system, humans are active in many roles, e.g., as function bearer and part of a functional unit, planner, communicator, team member, decision maker, leader, actor, responsible person, weak link, problem solver, element of the human-machine interface, knowledge bearer, observer and interpreter, threat and protection, resource and limiting factor.

Different roles, or pairs of roles, need to be considered, such as the experienced versus the inexperienced users; the designers versus the users; the hardware designers versus the software designers; the function designers versus the safety designers; the safety managers versus the security managers; the product managers versus the process managers; the operator versus the manager; the regulator versus the salesman and many more.

The development of a product or system aims to satisfy the needs of several people, groups, institutions or documents and sets of rules (e.g., standards or law), whereby the needs and demands can be very different, even contradictory. All these roles, people and institutions are referred to as stakeholders. Stakeholders serve the purpose of abstraction, in that a stakeholder represents the summary of all persons with the same interests, the same needs and the same view of the system. Stakeholders are thus persons and institutions that are affected in some way by the development and operation of a product or system. This also includes persons who are not involved in the system development, but who, for example, use the new system, keep it in operation or train it. Stakeholders are the information providers for goals, requirements and boundary conditions for a system or product to be developed.

Stakeholders of a project are all persons who have an interest in the project or are affected by it in some way as described in ISO 10006 (ISO 2018).

A distinction is made between active and passive stakeholders. Active stakeholders work directly on the project (e.g., team members) or are directly affected by the project (e.g., customers, suppliers, company management). Active stakeholders are usually structured according to the groups described in Table 10 in the project environment analysis.

Passive stakeholders are only indirectly affected by the project implementation or project impacts (interest groups, residents in a construction project, family members of project staff, associations, etc.).

The differentiation into active and passive stakeholders serves to structure the various stakeholders and thus supports the identification process. Subsequently, the importance for the project is determined via the stakeholder analysis. The factors influence on the project (power) and attitude towards the project (goals) are examined. The result of the stakeholder analysis is the foundation stone for the communication plan. In this section a brief overview of some of the relevant roles is given (Wirfs-Brock and McKean 2002; Sharon 2012; Anderson et al. 2019).

Table 10 Active stakeholders

Project manager
Project team members (core team and extended project team)
Customers, users
Clients
Sponsors and technical promoters

Novice and Expert

Novice and expert users have different needs, expectations, skills, and experience. New users often require guidance when using a system and need clear and obvious options because they have not yet developed a mental model of how the system works. Novice users rely heavily on step-by-step wizards or clearly labelled menus, for example, while more-experienced users learn keyboard shortcuts or touchscreen gestures to complete the same task. The expert users could still use the slower, more deliberate methods, of course, but get no benefit in doing so. Instead, they use a faster (but less guided) approach to the task. These faster, alternate methods of completing a frequent action are referred to as accelerators (Petre et al. 2016).

If a system caters primarily to new users by focusing on being very learnable, frequent users will be slowed down because the system likely includes a lot more step-by-step handholding than a frequent user would need. Therefore, the extra clicks to guide users through a wizard might be necessary to lead someone through a task the first time but extraneous for future repetitions.

On the other hand, if a system focused only on efficiency for expert users, it would probably be very difficult to learn. Keyboard combinations or performing a touch gesture are faster to execute than navigating through a sequence of menus to activate the same action but place a higher burden on the user's memory. Relying only on them would be like ditching a graphical user interface (GUI) altogether for a command-line one. With multiple methods to accomplish, the same task according to one's preferences or with accelerators that do not slow down inexperienced users, but speed up advanced users, the system becomes more flexible and efficient.

It requires extensive knowledge and experience to design a product or system in such a way that beginners and experts can use it adequately. This corresponds to the requirements of ISO 9241 (ISO 2019) on the aspects of user support (e.g., learning opportunities).

Designer and User

The task of a designer includes the creation of new products and services or variants of existing products and services. This requires him or her to keep up to date with the latest research and technology. He or she develops technical concepts based on which he or she, usually together with colleagues, plans and finally carries out the technical implementation. At least an initial model or development sample is created, followed by prototypes. This is used to dismantle and check the functionality of the newly realised or modified product. In this way, the strengths and limitations can be drawn, but also possible errors or weaknesses can be identified and, if necessary, improved before series production begins (Frankenberger et al. 1998).

Designers work together with colleagues from different areas (construction, ergonomics, manufacturing). Once the product is ready for the market, they also support marketing, for example by visiting customers. Designers are problem solvers. They understand a problem and find ways (products and service) to solve it now and in the future (Frankenberger et al. 1998).

A user, or end user, or operator, is a person who uses tools, aids, or work equipment to achieve a defined benefit. The user stands at the human-machine (or human-system) interface and operates the device. The machine can be a simple device (e.g., a hammer or a telephone) or a very complex system (e.g., a car, an airplane, or a power plant). In the context of complex systems, a distinction is often made between users, who make use of a system to perform their tasks and are thus in direct contact with the machine, and users (usually not natural persons, but organisations), who are responsible for the acquisition and operation of the system (Travis 2019).

In the classical design approach, the product is developed according to the requirements formulated and ordered by the user. The user is not involved in the development phase itself. He accepts the product after its completion. If the product does not meet the expectations, a problem arises. Who is to blame? Did the user not formulate the requirements, or did he or she not formulate them correctly enough? Did the designer not implement the requirements correctly?

It is indeed very difficult to know all the requirements for a product at an early stage and to describe them in a way that is easy to understand (and to implement). In practice, it is therefore often the case that the designers according to their own ideas and expectations interpret unclear and incomplete user requirements (Baxter et al. 2015).

This procedure, with all its problems, is often still the state of the art. Moreover, the usability, but often also the safety of the products is limited by this and a market success is prevented.

For this reason, there have been attempts for some time to better identify and better describe the requirements of the users (which they themselves sometimes do not know exactly) (Ulrich and Eppinger 2019).

User-centred design, or more comprehensive and holistic human-centred design, attempts to make product development interactive. The interaction takes place across different organisational boundaries and not only between designers and users (Felekoglu et al. 2013; Cross 2011; Kuang and Fabricant 2019).

The aim is to achieve what people really want and need. This is essentially obtained by placing the (mostly future) users of a product with their tasks, goals, and characteristics at the centre of the development process. In human-centred design, the product is optimised in collaboration between designers and users according to how the users can, want or need to use the product. Users should not be forced to change their behaviour and expectations to fit the product, but rather the product (or service) should adapt to the users.

The focus on users is thus twofold.

Focus one includes the context of the product, the goals of its development, and the environment in which it will be used. Focus two covers in more detail the users' task details, task organisation, and task flow.

The term user-centred design from the 1990s (e.g., also with Design Thinking (Cross 2011)) is more and more replaced by the terms Usability Engineering

Table 11 Phases of human-centred design process (ISO 2019)

Analysis of the context of use: During the analysis of the context of use, information is collected – together with the future users – about types of use. This is summarised in user profiles. These analyses also contain information about tasks, goals, work processes, work environment and the technical framework conditions of the users or the use
Definition of requirements: Based on the findings of the context analysis, requirements are defined to be implemented by designers and designers during the design process
Conception and design: In this process phase, concepts for the future product are developed and elaborated in iterative feedback between designers, designers, and users until a complete design (as design documents, mock-ups or paper prototypes) is achieved
Evaluation: The created concepts, designs, mock-ups, and prototypes are repeatedly discussed and tested with users. The goal is to ensure that the requirements, expectations, and possibilities of the users are met by the product (or service)

(Nielsen 1993; Kortum 2016; IEC 2015), human-centred design or community-based design (Norman 2021).

The iterative procedure of the human-centred design process goes through several phases, as they are described for example in ISO 9241 (here: user-centred) in Table 11 (ISO 2019).

Process Roles

Ultimately, engineering systems design is a part of overall product management. In companies and organisations, product management is a function that deals with the planning, management, and control of products (or services) during the product life cycle from first ideas and sketches, through market maturity to market exit.

Various procedure models are used to describe the development processes or to implement them in structural and procedural organisations and processes accordingly. A procedure model organises a process of design production into different, structured sections, which in turn are assigned corresponding methods and techniques of the organisation. The task of a procedure model is to represent the tasks and activities generally occurring in a design process in a logical order that makes sense. With their specifications, process models are organisational aids that can and should be individually adapted (tailoring) for concrete tasks (projects) and as such lead over into concrete action planning. Within the framework of these process models, different roles are described and defined, which have a share in the control of the processes.

One example of a proven process model is V-Modell XT (Rausch and Manfred Broy 2007). It is a representative of the so-called waterfall models. Waterfall models are linear (non-iterative) process models of hardware and software development that are organised in successive project phases. As in a waterfall with several cascades, the results of one stage fall into the next and are binding specifications there.

V-Modell XT is a process model for the implementation of IT projects, especially for the development of software systems. It supports the work of projects by specifying results and processes so that at no time unnecessary work and, if possible, no idle times arise. In addition, V-Modell XT regulates the communication between customer and contractor to eliminate typical sources of misunderstandings between the parties involved.

V-Modell XT defines project roles and organisational roles including tasks, authorities, capability profiles, responsibilities, and participation.

V-Modell XT defines different roles for the creation of products. Employees with specific roles participate in the creation of products or results by activity or are responsible for the creation. V-Modell XT defines process modules for easy handling of activities, products and roles. In tailoring, these process modules are defined as modular units via project types, project type variants and project characteristics.

Basically, V-Modell XT differentiates between two role categories: Project roles and organisational roles.

The organisational roles are – as the name already indicates – not located in the project but in the organisation. For example, they take care of acquisition, purchasing, data protection, IT security, etc. For each role, there is a specific role description, which covers a maximum of five points (Table 12).

In a concrete project, an employee can take more than one role; otherwise, it would not be possible to carry out small and medium-sized projects with V-Modell XT. Organisations should only take care to avoid conflicts of interest; for example, an employee should not be both project manager and QA (Quality Assurance) manager at the same time. In addition, mixing the organisational and project roles could become difficult if, for example, the data protection officer (as an organisational role) is simultaneously active as data protection officer (as a project role).

Designers and users, as the most likely relevant roles in the development process, are only two role types among many others.

Scrum is a process model representative of agile project and product management. It was originally developed in software technology but is independent of it. Scrum is used in many other areas and is regarded as the implementation of lean development for project management (Sutherland et al. 2019).

Scrum also defines different roles that are very close to the idea of the human-centred approach.

The Scrum Master role supports the process for the team. He accompanies the team and ensures that the right process is used. If there is a need for additional training, the Scrum Master organises the appropriate training. The Scrum Master is also responsible for all meetings. The same applies to organising practical things like the workplace, software, and hardware. He is therefore the one who ensures that the

Table 12 Specific role description in V-Modell XT

Task and power,
Skill profile,
Cast of characters,
Responsibility and
Participation.

team can work undisturbed. The Scrum Master must avoid that others interfere with additional requirements or tasks.

However, the Scrum Master is not a project manager (in the sense of the V-Modell XT). To promote openness and cooperation, he does not deal with personnel matters. He has nothing to do with the selection, evaluation, and remuneration of team members.

The Product Owner role represents the interests of the customer. Whoever fills it out is the client. If necessary, this can also be the customer himself. Because the customer has the greatest interest in the product being developed and being of high quality. After all, he pays the bill.

The Product Owner also manages the backlog. He decides what must be done and in what order. The most important wishes always come first. After all, they provide the greatest benefit.

The team is multidisciplinary. Because at the end of each sprint it must deliver a product. The team members ensure that the product meets the customer's requirements. In addition, that it is produced within the sprint. A team usually consists of three to nine people who organise themselves. The team does all the work that has to do with the product. From analysis, design, development and testing to documentation.

From a psychological point of view, people have a variety of formal but mainly informal roles in systems engineering. Some of these can also be taken on simultaneously. Objectives and procedures can also contradict each other.

The designer must find his place in all forms of organisation. The user often has the hardest time because he is not directly represented in the development process. The user often exists only in the form of his requirements or in the form of an abstract idea of his possibilities and limitations.

However, it is primarily the role of the designer (he or she develops the product) and of the user (his or her needs and expectations define the requirements) that are to be supported as effectively and efficiently as possible.

More Roles and Stakeholders

Depending on the perspective on the processes of engineering systems design, different approaches can be defined as to how possible roles can be defined, considered, and used within the framework of the different life phases in the product life cycle.

Typical Roles in Industry

In his research, Belbin (Belbin 1993, 2003) has analysed human behaviour in teams more closely with regard to the questions: How well (or less well) do teams work depending on the team composition? How should an optimal team be composed? By expertise? Experience? Sympathy? And how can strengths and weaknesses be balanced as well as possible?

Belbin's role model tries to answer these questions. It assumes that people behave differently depending on their personality traits and take on a typical role. A role is to behave in a certain way and to cooperate with others.

According to Belbin, teams work effectively when they consist of a variety of heterogeneous personality and role types. In his outline, he distinguishes three main orientations, each of which in turn encompasses three of the nine team roles (see Table 13).

Three action-oriented roles: Doer (Shaper), Implementer (Implementer), Perfectionist (Completer, Finisher).

Three communication-oriented roles: Coordinator/Integrator (Co-ordinator), Teamworker (Teamworker), Resource Investigator (Resource Investigator).

Three knowledge-oriented roles: Innovator/Inventor (plant), Observer (Monitor Evaluator), Specialist (Specialist).

Advantages and benefits of the model:

- Team members can better understand their own behaviour.
- Team members can work specifically on their weaknesses – awareness is the first step to start a reflection on the own thinking and acting.
- Leaders better understand the behaviour of their team members and can assign them appropriate tasks.
- Leaders can specifically compose teams in the way that is fitting with the current a balanced team.
- All participants know about different kinds of behaviours and can address each other's strengths and weaknesses.
- Mutual understanding of team members strengthens the cooperation in the team.

Table 13 Relevant roles in engineering systems design in the Belin Model (Belbin 2003)

The Monitor Evaluator (thought-oriented): Monitor Evaluators make decisions based on facts and rational thinking as opposed to emotions and instincts
The Specialist (thought-oriented): The Specialist is a team member who is an expert in a specific field
The Plant (thought-oriented): Plants are free-thinkers and creative people who produce original ideas and suggest innovative new ways of doing things
The Shaper (action-oriented): Shapers are extroverts who tend to push themselves and others to achieve results
The Implementer (action-oriented): Implementers are organisers who like to structure their environments and maintain order
The Completer/Finisher (action-oriented): Completers, also called Finishers, are introverted individuals who perform quality assurance during key stages of a project
The Coordinator (people-oriented): Coordinators are mature individuals who have excellent interpersonal and communication skills
The Team Worker (people-oriented): Team Workers are normally extroverts with mild and friendly dispositions
The Resource Investigator (people-oriented): Resource Investigators are extroverts who have a talent for networking

Weaknesses of the model:

- The approach of composing a team according to roles is in practice often not possible – instead, work is done with existing resources.
- People behave differently depending on the environment and the task – different roles can be assumed depending on the team.
- The transitions between roles are fluid – hardly anyone finds themselves in just one role.
- The scientific relevance is doubtful; there are only a few attempts to independently verify the role model, or the verifications only confirm it to a limited extent (Bednár and Ljudvigová 2020).

Besides the formulated strengths and weaknesses, there are psychological factors such as competition and personal dislike that cannot be controlled by assigning team roles.

Despite the weak scientific confirmation of the model, it is used in many areas of industry, administration and business and shows – at least – a plausibility benefit. Managers, developers, and project leaders are encouraged to think in a more differentiated way about roles and functions in development projects and in the life cycle of systems.

Psychological Functional Roles

With the perspective of psychological processes, roles can be identified, (see Table 14), that are oriented towards the content-related and psycho-social tasks (Dörner 1997; Badke-Schaub et al. 2011b; Schaub 2020).

These psychological roles are usually not planned or defined in a formal process. They emerge based on individual, psychological factors and situational demands. In the end, it is not the formal roles (e.g., the formal leader) but the informal, psychological roles (e.g., the informal leader) that determine what happens. In the best case, informal and formal roles coincide. It is often the case that the informal roles are more or less known, and an experienced (formal) leader knows how to use this. It becomes critical when the importance of the informal roles is ignored (Badke-Schaub and Frankenberger 2003; Friedman 2003).

Example in a Systems Engineering Organisation

The roles – for example – in a Systems Engineering Organisation for space systems can be broken down from the Chief Systems Engineer to the level of the individual Software Systems Engineer. At the upper level are the roles (and thus responsibilities) for:

System Design and Integration Lead, Payload Systems Lead, System Requirements Lead, Mission Operations Lead, System Verification & Validation Lead, Risk Manager and at the lower levels the horizontal integrators: Software Systems Engineer, Mechanical Systems Engineer, Guidance & Control Systems Engineer, Navigation Systems Engineer, Comm Systems Engineer, Avionics Systems Engineer.

Table 14 Psychological roles and functions in engineering systems design (Dörner 1997; Badke-Schaub et al. 2011b; Schaub 2020)

The human being as an integral part of every (socio-technical) system. People are a building block in an engineering systems design approach. This very comprehensive HOT (Human, Organisation, Technology) perspective allows to analyse, design, develop, and operate the different requirements of a systems design at the comprehensive level
The human being as a part of a functional unit. In this perspective, the human being is seen exclusively as a functional link and is assessed under functional criteria (e.g., in terms of strength, speed, and error rates)
The human being as planner. The human being designs and thinks ahead of processes and actions
The human being as communicator. The human being is seen primarily in terms of his or her exchange of information
The human being as a team member. The human being has a position and function (formal and informal; professional and psychological) within a cohesive group, e.g., in a department or project
The human being as decision-maker. The human being is responsible for processes and organisation. S/He directs and controls others in their work. The human being is first and foremost a manager
The human being as leader/guider. The human being is a role model and guides through visions and strategies
The human being as a maker. The human being is seen primarily as an implementer of ideas, not as a creator of ideas
The human being as a responsible person. The human being is responsible for his actions and those of the co-workers, in the sense of hierarchy, legally, psychologically and morally
The human being as a weak link. In the case of problems (e.g., efficiency breakdowns) or accidents, but also in the case of cost and resource issues, people are often the ones who are seen as slow, weak, faulty, and too expensive
The human being as problem solver. When technology fails, processes do not work or the organisation does not perform as it should, the human being as system operator, pilot, operator, developer is often the one who can analyse and save the situation
The human being as an element of the human-machine interface. Humans are often reduced to their purely bio-mechanical attributes and seen as part of a large machine
The human being as knowledge carrier. Despite all the databases, internet sources and knowledge bots, people with their process and contextual knowledge are the most important knowledge resource of a company
The human being as observer and interpreter. Humans can act, or just observe and analyse
The human being as threat and protection. It is often not clear whether humans threaten processes and systems because of their mistakes and errors, or whether they protect them because of their cognitive and sometimes social capabilities. Often both is probably the case at the same time
The human being as resource and limiting factor. Human flexibility (be it, e.g., the biomechanical flexibility of the hand, be it, e.g., the cognitive problem-solving ability) is, despite all limitations of the human being, an important resource because it can be used universally

These roles resulted from the requirements that Lockheed Martin Space Systems Company had to fulfil in its projects for and with NASA. Roles are not carved in stone and must be adapted to current requirements and unforeseen situations.

It is critical when roles are not flexibly adapted to the content-related and social circumstances – projects go wrong, schedules are not met, quality drops. Customers, employees, and management become increasingly dissatisfied. Processes and organisation become inefficient, employees leave the company or go into internal immigration.

Example: Roles and the Human-Robot Collaboration

The question of the roles involved in the Human-Robot Collaboration (HRC) arises in many ways. Of course, all roles are involved, as in any technical design and application context. But this example also gives rise to interesting new aspects, e.g., regarding the dynamic role allocation:

– Human-Machine Task Allocation: Dynamic procedures to control the task allocation between humans and robots in the respective situation according to the respective capabilities and limitations.
– Cognitive Dummies: Standard and critical situations in collaboration can be represented via simulation and augmented reality to analyse them, readjust the behaviour of the robots, improve the human-system interface or sensitise and train the people.
– Quality time or brain-on-task time: Appropriate human-robot collaboration also means that valuable time is gained for humans through task performance by robots, who can use it for problem solving, creativity or empathic, social contacts, for example.

Conclusion

The context of engineering systems design is becoming increasingly complex. At the same time, the number, duration, diversity, and intensity of projects are also increasing the pressure on the efficiency and effectiveness of the persons deployed. To this end, complex specifications and technical systems are developed in projects within the framework of organisational and process specifications and use. However, in critical situations, it is the human being who decides, not the machine – and often under time pressure, information deficits and high risk (Badke-Schaub and Frankenberger 2003). The human being is not primarily to be supported in the sense of avoiding disruptions, but above all in the sense of optimising the quality, efficiency and effectiveness of product and system development. The importance of people such as designers, managers, end users or customers is increasing, both in the world of networked, global digitalisation and in the context of increasingly complex development projects (Frankenberger et al. 2020). The possibilities and expectations of new technologies' present designers and users at all hierarchical levels with unfamiliar, undefined, and unexpectedly stressful and critical situations for which there are no routine answers. These places rapidly increasing demands on the ability of everyone to think, plan, make decisions, lead and act. Human Factors play a role, for example, when modern projects aim to optimise the organisation, processes, and procedures. This must necessarily have an impact on the areas of personnel selection, initial, further, and advanced training, the design of work systems and human-machine interaction as well as organisational development. Humans as actors in complex systems, including as designers and as users, not only face operator and user problems but modern systems also expand their scope of action and thus the complexity of their interaction possibilities with the systems and the people participating in or are affected by them. In the age of digitisation, Human Factors primarily concern the use and handling of modern interaction and communication media and processes, their networking and digitisation, and the limits and possibilities of a comprehensive information and communication technology network. In particular, the focus is on leadership, decision-making and action in highly complex and uncertain situations. The processes of change, adaptation, but also the tendencies of people and organisations forms to persist in a system that must constantly adapt to changing social and technical conditions play an essential role. New developments in design methodology and philosophy of technology can be used in a supportive way (Vermaas et al. 2008; Badke-Schaub et al. 2011a; Cross 2021), although some of the expectations of the possible influence of designers in a better world may be too high. This chapter focuses on various components and aspects of human beings involved in engineering systems design in general and outlines human behaviour, managerial processes and formal and informal roles in particular.

Cross-References

► Asking Effective Questions: Awareness of Bias in Designerly Thinking
► Creating Effective Efforts: Managing Stakeholder Value
► Data-Driven Preference Modelling in Engineering Systems Design
► Designing for Emergent Safety in Engineering Systems
► Designing for Human Behaviour in a Systemic World
► Designing for Technical Behaviour
► Digitalisation of Society
► Engineering Systems Design Goals and Stakeholder Needs
► Ethics and Equity-Centred Perspectives in Engineering Systems Design

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Risk, Uncertainty, and Ignorance in Engineering Systems Design

10

Josef Oehmen and Jan Kwakkel

Contents

J. Oehmen (✉)
Department of Technology, Management and Economics, DTU-Technical University of Denmark, Kongens Lyngby, Denmark
e-mail: jooehm@dtu.dk

J. Kwakkel
Faculty of Technology, Policy and Management, Delft University of Technology (TU Delft), Delft, Netherlands
e-mail: j.h.kwakkel@tudelft.nl

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Abstract

Uncertainty is the third major perspective in understanding and designing engineering systems, along with complexity and human behaviour. Risk, a corollary of uncertainty, is understood as the effect of uncertainty on objectives. When designing engineering systems, you cannot not manage risk – even ignoring risk equates to a decision to accept it. Engineering systems are characterised by long life cycles, changing operational environments, and evolving stakeholder values, leading to a wide range of uncertainties in their design and operation. Productively engaging with this uncertainty is critical for successfully operating and especially (re-)designing engineering systems.

This chapter provides an overview of managerial practices to address the three levels of increasing uncertainty in engineering systems design: from (1) managing risk, to (2) managing uncertainty, to (3) managing ignorance. We differentiate for each level of uncertainty between two levels of value diversity: (1) primarily commensurate values (i.e. agreement on core values by critical stakeholders) and (2) primarily incommensurate values (i.e. no agreement on core values). The managerial practices we discuss are "classic" risk management, public engagement, scenario planning, robust decision-making, resilience, and applying the precautionary principle. In addition, we briefly illuminate the actuality of management practices dealing with the different levels of uncertainty beyond explicit, formal processes, the understanding of managing uncertainty as both modelling and decision support practices and personal and organisational biases in the context of addressing uncertainty.

Keywords

Engineering systems · Engineering systems design · Resilience · Risk management · Robust decision-making

Introduction: Addressing Uncertainty in Engineering Systems Design – Conceptualising "Risk Management"

What Is "Risk Management" for Engineering Systems?

Traditionally, managerial approaches addressing various levels and types of uncertainty in decision-making are summarised under the label of "risk management." Broadly defined, risk management is an inclusive set of organisational practices to support decision-making during the design of engineering systems interventions under varying conditions of uncertainty. The simplest definition of risk is the effect of uncertainty on objectives (ISO 2018). Later in this chapter, we will differentiate between three levels of uncertainty (risk, uncertainty, and ignorance) and correspondingly introduce three categories of managerial practice, i.e. management of risk, management of uncertainty, and management of ignorance (see Fig. 2). It is worth pointing out that we understand ignorance simply as a technical term describing a lack of knowledge and information, without any implicit value judgement (such as "ignorance due to a lack of education" or "wilful ignorance").

There are many of both *sources of uncertainty* and their *impact categories* in the context of engineering systems design. The sources of uncertainty in engineering systems design fall into three major categories (Willumsen 2020):

1) Uncertainties originating from requirements are driven by a complex stakeholder landscape, lack of historical data, and long life cycles, including changing contexts of operation.
2) Uncertainties regarding technical feasibility originate from numerous and diverse subsystems and their interfaces, including their differing technology maturity and life cycles (e.g. innovation and obsolescence cycles).
3) Uncertainties arise from the organisational domain, i.e. our ability to plan and execute the design and implementation of engineering systems interventions, including our processes, skill levels, and organisational integration.

The impact categories in the context of engineering systems are as manifold as the objectives of engineering systems. These objectives range from cost and technical performance to societal value creation to environmental and sustainability impacts. This makes a unified quantification of impacts challenging, as different impact categories cannot easily be converted into one another (say, safety vs. sustainability risks). In addition, as we will explore later in this chapter, stakeholder groups hold diverging views on values and priorities, which must be accommodated in prioritisation and treatment of uncertainties.

As engineering systems designers, we cannot not manage risk, uncertainty, or ignorance. Even if individuals or organisations make a conscious decision not to engage in risk management and ignore, say, uncertainty regarding future market demands, they will have made a risk management choice: to accept to absorb the full and unmitigated range of consequences of the risks in their design task. The managerial practices of risk management, and by extension the management of uncertainty and ignorance, extend beyond formalised processes, as discussed by Willumsen (2020) and shown in Fig. 1: risk management activities can either be formalised (e.g. a risk identification workshop) or informal (e.g. a lunchtime conversation with a critical supplier). Furthermore, we can explicitly engage in risk management (e.g. reviewing our top ten risks), or we can implicitly engage in risk management (e.g. reviewing incomplete requirements). Combined, these two dimensions yield four domain management in practices:

- Formal, explicit risk management processes (the focus of this chapter)
- Informal, explicit risk management processes (e.g. ad hoc reactions to plan deviations or inclusion of design margins due to a "gut feeling")
- Formal, implicit risk management processes (all aspects of designing engineering systems interventions that address uncertainties and their impact, without formally calling them risk management, e.g. validation and testing)
- Informal, implicit risk management processes (such as building social capital and trust-based relationships among team members, suppliers and customers, etc.)

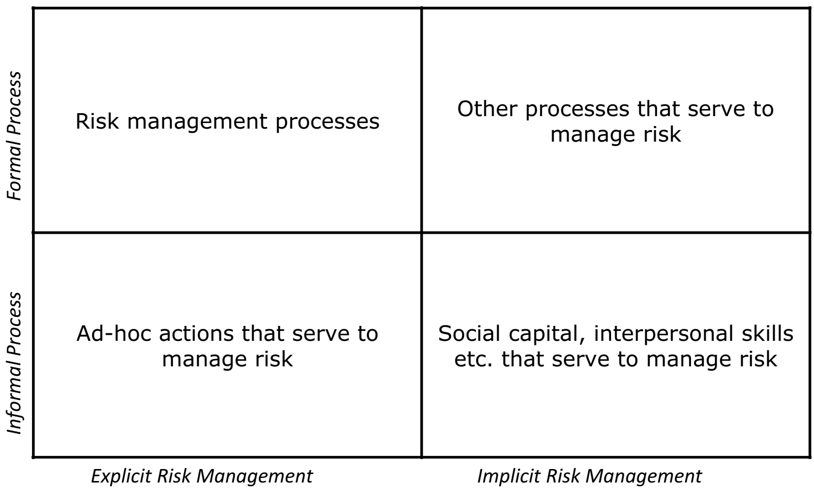

Fig. 1 Risk management is more than formal, explicit risk management processes (following Willumsen 2020)

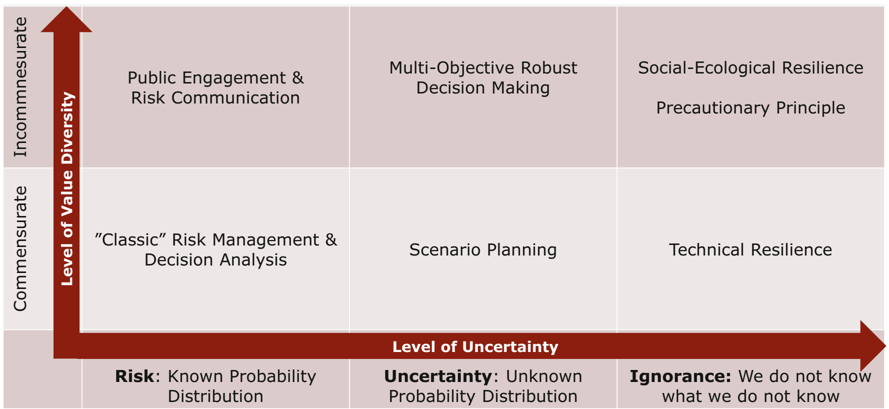

Fig. 2 Example practices for managing risk, uncertainty, and ignorance in engineering systems design

This chapter will primarily focus on formal, explicit management practices of uncertainties in the context of engineering systems. To be precise, we will discuss the management of risk, uncertainty, and ignorance into two social contexts: commensurate values, i.e. contexts where stakeholder values align, and incommensurate values, i.e. contexts where stakeholder values do not align. Additionally, we will briefly highlight decision-making and thinking biases in the context of uncertainty.

A Sociotechnical Perspective of Risk Management Activities

Levels of Uncertainty and Level of Value Diversity

When considering "risk management" activities in the context of sociotechnical systems, there are two essential aspects. First, we need to decompose the term "risk" (see section "Level of Uncertainty: Risk, Uncertainty, and Ignorance") to incorporate three distinct concepts regarding the "degree of uncertainty" that a decision-maker faces: risk, uncertainty, and ignorance. Second, we need to distinguish methods applicable in situations where there is general agreement across stakeholders regarding their values, versus management techniques applicable to deal with, or resolve, conflicting stakeholder values. We chose to focus on "stakeholder values" instead of "stakeholder objectives" in this chapter for two reasons: First, objectives are based on values, so we focus on the more foundational concept. Second, values represent true stakeholder preferences, whereas formally (and publicly) articulated objectives may be influenced by several other considerations and thus not truly representing preferences. A simple example of values impacting risk management is the question "How safe is safe enough?." This is discussed in section "Level of Value Diversity."

Management of Uncertainties as Modelling and Decision Support Practice

The discipline of risk management has long acknowledged that risk management is more than technical risk assessment practices. We can broadly discern two categories of management activities (see Table 1): first, activities aiming at understanding, describing, and modelling engineering systems and their constituent elements and relationships as they pertain to the management of risk, uncertainty, or ignorance. This includes an explicit description of the degree of knowledge, or uncertainty, captured, or not captured, by those models. Second, management activities that enable and support decision-making processes, including the communication and visualisation of risk, uncertainty, and ignorance-related models.

The two types of activities are closely linked: The results of what and how we model inform our decision support processes, while the specific requirements of our

Table 1 Examples of two types of management activities addressing risk, uncertainty, and ignorance

Management as models of engineering systems ("understanding risk, uncertainty, or ignorance")	Management as models of decision support processes ("managing risk, uncertainty, or ignorance")
• Physical or virtual prototypes and their user interaction • Specific functional models, e.g. system dynamics simulations • Specific risk models and simulations, such as Monte Carlo simulations • Specific risk assessment techniques, such as fault tree analysis or barrier models	• Risk governance frameworks • Risk management process frameworks • Visualisation and communication guidelines • Decision-making heuristics, such as the precautionary principle or risk acceptance criteria

decision support processes determine the requirements for our risk, uncertainty, and ignorance-related models. While there are approaches to modelling very different degrees of uncertainty, we argue that system model-based approaches become more prevalent as more data are available and consensus on stakeholder value increases (i.e. systems are better known or designs have progressed further). In contrast, process model-based management techniques for these levels of uncertainties tend to be more prevalent for situations with significant uncertainty and less consensus on stakeholder values.

Personal and Organisational Biases Regarding Risk, Uncertainty, and Ignorance

Basic economic theory assumes that humans, and by extension organisations, are efficient and rational decision-makers, dependably making choices in their own best interest, i.e. maximising expected utility according to their own articulated criteria. However, as experiments and empirical data on decision behaviour clearly show, the reality is much more complex. This is particularly present in decision-making under uncertainty.

This led to, among others, the development of prospect theory: To account for changes in decision-making behaviour under uncertainty, utility theory-based choice models are replaced with value functions based on gains and losses (not to assets), and the role of probabilities is replaced by decision weights. This leads to value functions that are now concave for gains and convex for losses, accounting for real-life decision-making behaviour under uncertainty (Kahneman and Tversky 1979). Kahneman (2011) popularised a model of decision-making that discerns between two types of thinking: "fast thinking," or type 1 thinking, describes intuitive, quick, and mostly subconscious decision-making processes. "Slow thinking", or type 2 thinking, describes deliberate, analytical decision-making processes based on data and transparent decision criteria. Early discussions of type 1 thinking include using heuristics that extend past experiences to novel phenomena and lead to unreflected and possibly misguided intuitive decisions, expressed as representation bias, availability bias, or anchoring bias (Tversky and Kahneman 1974). Choices become skewed from what basic economic theory would predict, e.g. overweighting both very high and very low probability events relative to moderate probability events. Risk attitudes, i.e. risk aversion and risk-seeking behaviour, are different if decision problems are framed or perceived as chances of loss or chances of gain (Kahneman and Tversky 2013).

Other authors emphasise the value (and necessity) of "fast thinking," especially the use of heuristics as an enabler of decision-making under conditions of complexity, time constraint, and bounded rationality of the decider (Gigerenzer and Goldstein 1996; Gigerenzer and Selten 2002). This is important to keep in mind in the context of "real-life" risk management in the context of engineering systems: Just because theoretically, there may be a data-intensive analytical process available to us does not mean that pursuing a "slow thinking" decision is the best choice under all circumstances. Having said that, this chapter does focus on formal decision-making frameworks. For example, in the context of project risk management, these have been discussed and reviewed by McCray et al. (2002) and Stingl and Geraldi (2017).

Equally relevant to biases and heuristics in decision-making under uncertainty is the matter of public (technology) risk perception or, maybe better, risk-benefit perception (Fischhoff et al. 1978). One of the particular biases affecting risk-benefit perception is the affect heuristic (Slovic et al. 2007), leading, for example, to a lower inferred risk if the benefit of an option is perceived to be high and reversely, leading to a low inferred benefit if an option is perceived to have high risk.

In their review article, Renn and Benighaus (2013) identify several underlying factors shaping risk-benefit perception, including attention and selection, the use of cognitive heuristics (see above), evolutionary coping strategies, cultural patterns, and semantic images. Factors shaping individual risk perception, for example, depend heavily on the perceived degree of control, whether the exposure to the risk is voluntary, and whether the risk is novel (Slovic 1987, 2010). Tightly coupled to the question of individual risk perception is the phenomenon of "social amplification of risk" (Kasperson et al. 1988).

Level of Uncertainty: Risk, Uncertainty, and Ignorance

The words "risk" and "uncertainty" have a very long history, with these terms being used already in, for example, roman times when discussing business endeavours or harvests. As discussed earlier, ISO 31000 links the two in its definition of "risk as the effect of uncertainty on objectives" (ISO 2018). Its modern history begins with Knight (1921), who introduced a sharp distinction between risk and uncertainty. For Knight, risk is calculable, while uncertainty is not. That is, if one faces a choice where the consequences and their probability of occurrence are known, Knight calls it risk. If either the consequences or the probability of occurrence is not known, Knight calls it uncertainty.

In the mid-1950s, the sharp distinction drawn by Knight started being questioned. Knight focuses on whether probabilities are known, but what if, instead, probabilities merely reflect degrees of belief? Suddenly, a much broader range of phenomena can be treated following a risk-based approach. This idea of seeing probabilities as beliefs is also known as a Bayesian interpretation of probability, and it has substantially increased the use of risk-based approaches (Bolstad and Curran 2016).

In light of recent developments such as climate change and the financial crises, there is now a resurgent interest in uncertainty proper, or Knightian uncertainty. That is, not everything can be reduced to risk using beliefs. What if different people have different beliefs? What about the evidential basis for beliefs? And how to make sense of the frequency with which surprises happen?

In this chapter, we follow the Knightian distinction between risk and uncertainty but add a third category, namely, ignorance. Decision-making under ignorance and without foresight is a concept first explored in ecology, where populations of organisms can be highly successful over time without being able to predict the future. As pointed out earlier, we understand ignorance as a simple technical term describing a lack of knowledge and information, without any implicit value judgement (such as "ignorance due to a lack of education" or "wilful ignorance").

The threefold distinction we are using (see Table 2) is broadly coherent with similar levels of uncertainty as can be found in, for example, Walker et al. (2003, 2013) and Kwakkel et al. (2010). The main difference is that we use a threefold distinction, while many conceptualisations of the level of uncertainty make additional, more fine-grained distinctions.

Table 2 Levels of knowledge and resulting theoretical and practical challenges. (Adapted from Oehmen et al. (2020))

Definitions	Theoretical challenges	Practice challenges
1. Management of risk • Risk: Possible outcomes with known probabilities (Knight 1921) • Conditional probability (Bayesian statistics): Incorporating prior believes into risk assessment (Bolstad and Curran 2016) • Risk management: Coordinated activities to direct and control an organisation regarding its risks (ISO 2018)	• Conflicting definitions of "risk" and "risk management" (Aven 2012, 2016; Aven and Renn 2019) • Articulation of organisational value of risk management (Willumsen et al. 2019)	• One-size-fits-all expectation of risk management standards vs. need for customisation (Oehmen et al. 2014) • Idealised formal risk management neglects actual risk management (including its informal aspects) (Ahlemann et al. 2013; Kutsch and Hall 2010) • Choice of appropriate risk management methods for given decision context and data quality (Tegeltija 2018)
2. Management of uncertainty • Uncertainty: Possible outcomes with unknown probabilities (Knight 1921) • Robust decision-making: Assessing performance across a broad range of possible futures to minimise regret (Walker et al. 2013)	• Delineation of uncertainty and risk (Aven 2012; Flage et al. 2014) • Development of some mathematically very advanced reasoning into actionable methods, while maintaining rigour (Tegeltija 2018)	• Incorporation and communication of uncertainty in decision-making (Funtowicz and Ravetz 1990) • Implementing and operationalising novel uncertainty management methods (Tegeltija 2018)
3. Management of ignorance • Ignorance: Unknown outcomes with unknown probabilities (Smithson 1989) • Resilience: The ability to resist or recover from unexpected events without foresight (Holling 1973)	• Theoretically sound operationalisation of resilience concepts into organisational practice (Wied et al. 2020a) • Reconciliation of expectation of productivity with need for resilience (Martin 2019)	• Articulation of specific and explicit resilience strategies for organisations (Wied et al. 2020a) • Orchestrate cultural shift from "predict and plan" to "monitor and react" (Kutsch et al. 2015; Rolstadås et al. 2011)

Level of Value Diversity

Risk management addresses the impact of uncertainty on objectives, i.e. the consequences of uncertainty (ISO 2018). What consequences matter and how to assign a value to them is a second dimension along which we can distinguish different approaches for managing risk. Classic decision theory assumes that all consequences can be aggregated into a single number of goodness, be it utility or monetary (Savage 1951). However, in many real-world situations, this assumption is problematic. Even if the different parties to a decision agree about what matters, they may still disagree about what is acceptable.

A classic example is the question "what is safe enough?." For example, in the context of flood risk management, we might all agree that we want to avoid floods. However, what is safe enough? How high should the embankments be, and at what costs? More severely, actors might care about quite different outcomes, and it might not be apparent at all how these different outcomes are to be aggregated into a single measure of goodness. Such aggregation is theoretically problematic (Arrow 1950; Franssen 2005; Kasprzyk et al. 2016), while often also a significant source of contestation (Rittel and Webber 1973) or ethically problematic (Taebi et al. 2020) (e.g. what is the value of a human life?). Continuing on the flood risk example, in Dutch water management practice over the last century, we can see a shift from focusing solely on flood risk in response to the 1916 floods, towards the consideration of environmental and socio-economic concerns next to flood safety in the evolving response to the 1953 flood, with environmental concerns taking centre stage in the mid-1990s (Correljé and Broekhans 2015). For ease of exposition, the remainder will distinguish between situations with commensurate values and incommensurate values. If values are commensurate, it is in principle possible to develop an uncontested and acceptable way of aggregating diverse outcomes into a single measure of goodness. If values are incommensurate, such an uncontested and acceptable procedure is ruled out.

An Engineering Systems Perspective on Managing Risk, Uncertainty, and Ignorance: Addressing Levels of Uncertainty and Levels of Value Diversity

In the following sections, we present an integrated view of engaging with different levels of uncertainty in engineering systems design that also accommodates different levels of value diversity among the stakeholders. This yields six quadrants, as illustrated in Fig. 2. Each quadrant is discussed in turn in the subsequent sections. We aim to present an overview of relevant risk, uncertainty, and ignorance management approaches (both system models and decision support processes) and illustrate their diversity; we do not aim to replicate the current bias in both application and academic publishing towards specific quadrants, especially the very intense use of methods describing risk under commensurate values. Some approaches, such as risk communication and public engagement, are relevant for multiple quadrants.

A general observation worth noting is that management approaches tend to offer higher fidelity system models as we move towards commensurate values and known probability distributions (the lower left-hand corner of Fig. 2). In contrast, the focus on general stakeholder engagement and decision support processes increases as we move towards ignorance and incommensurate values (the top right-hand corner).

Understanding and Managing Risk in Engineering Systems

Risk Under Conditions of Commensurate Values

The foundational concept of risk management is that risk can be expressed in the language of probability theory or more precisely, through frequency probabilities (see Bertsekas and Tsitsiklis (2008) and Blitzstein and Hwang (2019) for two introductory texts). They analyse the sample space of a random experiment and describe the occurrence of specific events in that sample space. The relative frequency of an event is defined as the probability of that specific event occurring in the sample space. The events being investigated are associated with a loss, leading to either a discrete description of risk, i.e. probability-loss pairs such as "the risk of exceeding the budget by 20% in the next 2 years is 5%," or continuous probability distributions expressed as probability density functions of a continuous outcome variable. These practices find broad application in engineering systems design, ranging from safety management to cost management to the estimation of future maintenance needs and user demand.

Frequency probabilities are well suited to capture aleatory uncertainty, i.e. uncertainty due to the inherent randomness of the natural world. However, to better capture epistemic uncertainty, i.e. uncertainty due to a lack of knowledge, Bayesian probability theory extends the concept of frequency probabilities to allow capturing and updating "beliefs" regarding future events (see Jaynes et al. (2005) for an introduction on Bayesian probability theory and statistics).

The ISO 31000:2018 "Risk Management – Guidelines" (ISO 2018) standard was developed to provide general risk management principles, an implementation and adaptation framework, as well as a reference process for risk management in organisations. It is deliberately not domain-specific to facilitate cross-functional integration of risk management processes. It provides a helpful reference framework to compare and reconcile various specific risk management activities. The main elements of the ISO 31000:2018 risk management reference process are:

- **Risk identification:** Identification and description of key risks within the scope of the risk management activities. Structured along sources of uncertainty as well as affected objectives.
- **Risk analysis:** Qualitative and/or quantitative modelling and description of risks in context. The specific methods and descriptions being used (e.g. point estimates vs. continuous probability distributions) depend on fundamental

scoping decisions (see below). This includes analysis of time-dependent (i.e. dynamic) factors, as well as sensitivities and confidence analysis.

- **Risk evaluation:** Categorisation of risks regarding the type of future action that will be taken to respond to them and associated decision support. It includes articulating actionable criteria or limits that inform decisions regarding risk responses. Other than directly influencing the probability of occurrence and/or impact of a risk, outcomes of risk evaluations are also a "do nothing" option, as well as additional risk analysis or adjustment of objectives.
- **Risk treatment:** The process of articulating and implementing risk responses, including setting up metrics to assess their effectiveness and risk re-evaluation (i.e. if a risk that has been responded to is now below the threshold for further action).
- **Monitoring and review of risk, mitigation, and risk management**: Monitoring maintains transparency during the risk management process, facilitates a continuous improvement process, and integrates the risk management process into quality management and other process management processes.

As well as contextualising management processes:

- **Communication and consultation during risk management:** Engagement of stakeholders to facilitate a common understanding of the risk landscape and risk management process but also to integrate expertise and experience into the risk management process.
- **Establishing scope, context, and criteria for risk management:** Customisation of risk management process towards the needs of key stakeholders, including scoping risk identification activities or articulating risk evaluation and treatment guidelines.
- **Recording and reporting risk management activities and outcomes:** Documentation and dissemination of key activities and outcomes of the risk management process, such as risk registers or mitigation actions.

There exist a range of engineering-specific risk management processes (see Table 3), including risk management processes proposed by NASA (Dezfuli et al. 2010; NASA 2014, 2017; Stamatelatos et al. 2002), risk management processes as part of systems engineering (Walden et al. 2015), project risk management processes (e.g. PMI 2017; TSO 2017), or a wide range of domain-specific safety management standards (e.g. the ISO 45000 family of standards).

The project management literature offers several risk management frameworks, for example, as part of the PMI *Project Management Body of Knowledge* (PMI 2017) or the PRINCE2 project management framework (TSO 2017). The focus is on project management-related risks (such as cost and schedule) and also addresses other organisational risks, external risks, and technical risks. Risk management aims to protect against adverse impacts on scope, schedule, cost, and quality.

There are also several risk management standards and guidelines that were developed by the NASA, focusing on developing and operationalising highly

Table 3 Overview of select risk management reference processes (see text for references)

ISO 31000	PMI	NASA	INCOSE
Risk identification	Identify risks	Identify risks	Analyse risks
Risk analysis	Qualitative risk analysis Quantitative risk analysis	Analyse risk	
Risk evaluation	Plan risk response		
Risk treatment	Implement risk response	Planning	Treat risks
Monitoring and review	Monitor and control risks	Communicate, control, and track risks	Monitor risk Manage the risk profile
Communication and consultation	*Implicit*		
Establishing the context	Plan RM	Develop strategy	Plan risk management
Recording and reporting	*Implicit*	*Implicit*	*Implicit*

integrated technical systems. This includes the NASA's *Risk-Informed Decision Making Handbook* (Dezfuli et al. 2010), guides for probabilistic risk assessment in the context of complex technical programmes (Stamatelatos et al. 2002), or formal risk management process standards (NASA 2014, 2017). Risk here is defined as the potential for performance shortfalls of the system under development. It considers safety, technical (i.e. technical performance), cost, and schedule risks.

The INCOSE risk management recommendations also focus on the development of complex systems. It considers technical performance, cost, schedule, and programmatic risks (the last one describing a source of uncertainty instead of an impact category). It embraces simple point estimates for risks and addresses human factors such as risk perception and the fact that different risks may hold different importance among stakeholders.

A central shared assumption of these risk management approaches is that stakeholder value, while it may differ to some degree from stakeholder to stakeholder, can ultimately be expressed as a quantifiable measure of *utility* (Pratt 1964).

The foundation of modern-day risk analysis is the idea of subjective expected utility as axiomatised by Savage (1954). According to this theory, an individual decision-maker who adheres to the axioms of rationality has both a personal utility function and a personal probability distribution (typically Bayesian, hence subjective). The optimal decision is then the one that maximises the expected utility. Experiments with people have shown that people deviate systematically from the correct decision according to subjective expected utility theory (Kahneman 2011). This has given rise to various bodies of work that try to explain these systematic deviations of real-world behaviour from what is considered correct according to subjective expected utility, for example, through heuristics and biases. More recently, Savage has been criticised from a more mathematical point of view: there is a fundamental difference between the expected value over time and the expected value across events (Peters 2019). For example, if we have 100 fair dice, the expected value will be the same as the expected value of rolling one of these dice 100 times. If, however, we have 100 unfair dice, the expected value over the ensemble of dice is not the same as the expected value of rolling one die 100 times.

For engineering systems design, the concept of systemic risks is also relevant. Systemic risks describe a situation where failures of single or multiple components cause a cascading effect that will degrade (or completely negate) system-level performance (Acharya et al. 2017). As a concept, it originated and is well established in in the financial sector, describing risks where the collapse of single (or very few) financial institutions can cause the breakdown of an entire country's or region's financial system (de Bandt and Hartmann 2001). While extensively studied in the context of financial systems (Fouque and Langsam 2013), the application of the concept of systemic risk beyond financial system is still scarce (Gros et al. 2016).

Risk Under Conditions of Incommensurate Values

Under conditions of incommensurate values, our fundamental philosophical world view becomes highly relevant: Do we adopt a positivist attitude (Wicks and Freeman 1998), where a fact-like "true" answer exists, or do we take a social constructivism perspective (Kukla 2000), where the correct answer becomes everything depends on how each individual perceives reality and makes sense of it? This is highly relevant in engineering systems design, for example, regarding the legitimacy and cost justification of large engineering systems interventions, or the comparative safety merits of alternative technical and organisational choices.

Risk management rooted in the technical and natural sciences has a natural bias towards a positivist, fact-based, or "technocratic" worldview: With enough analysis and conversation, everyone will agree to the numbers on my Excel sheet, including the overall optimal priorities and weights. Effectively, the belief is that incommensurate values are just poorly analysed commensurate values and can be transformed into those. The risk management process frameworks discussed in the previous section cover this approach under "communication and consultation."

Under conditions of incommensurate values, we have to embrace a post-positivist stance (Geraldi and Söderlund 2018) in order to resolve the paradox of both respecting and accommodating individual perceptions of risk (and reality) while at the same time implementing a structured and objectively controllable risk management process. This section will briefly illuminate three relevant bodies of work in this context: risk-related public engagement, risk communication, and social movement theory.

Public engagement or public participation is a highly relevant field once we accept that risk management is a discursive process in situations of incommensurate value. Public engagement can yield similar benefits to a co-creation process, in leveraging both collective knowledge and creativity and creating buy-in and ownership with the engaged stakeholders (Sanders and Stappers 2008). However, they may also yield the opposite result and create anger and mistrust if they do not meet quality standards and stakeholder expectations (Innes and Booher 2004; Rowe and Frewer 2000). Public engagement can be differentiated into communication, consultation, and engagement and their associated methods (Rowe and Frewer 2005). Engagement of the public will always be shaped by the existing knowledge and reflection of the groups that are being engaged and requires careful consideration when developing engagement formats (Whitmarsh et al. 2011).

Closely linked to public engagement are risk communication and its corollary, risk perception. It forms part of every engagement process. A practical and fair risk communication process respects our natural risk perception biases (see section "Personal and Organisational Biases Regarding Risk, Uncertainty, and Ignorance" in this chapter) while preparing a "slow thinking" engagement with the subject matter. The opposite is, however, much easier: exploiting our natural perception biases to amplify risk perception. Therefore, responsible risk communication has a dual role of addressing the subject matter at hand and being part of improving the quality of societal discourse by demonstrating and training appropriate communication methods. Some of the most relevant factors include the following (Kasperson 2014; Renn and Benighaus 2013; Wachinger et al. 2013):

- Personal experiences of specific risks are the strongest communication and powerfully shape the risk perception of individuals.
- Trust in the communication relationship is also highly relevant. It is a foundational factor in enabling fact-based risk communication. It is arguably much more significant than "facts." This becomes particularly challenging if there is a perceived conflict of interest by one of the parties, e.g. a company arguing for the safety and benefit of their own products.
- One element influencing trust is the open communication of the quality of a risk assessment, for example, through the NUSAP model (Funtowicz and Ravetz 1990). It makes risk assessments more credible by providing context information on the origin and quality of data, the underlying model, and the experience of the assessors.
- A paradoxical observation is that a high personal perception of risk does not necessarily translate into action. This is particularly relevant if the objective of the communication is to incentivise action, such as personal or organisational preparedness. The reasons for inaction also highlight options for accompanying action and include (1) acceptance of risk, as perceived benefit significantly outweighs perceived risk; (2) denial of agency for taking mitigation action, i.e. "not my problem to solve"; and (3) perceived lack of sufficient resources to take action.
- Media exposure to risk and risk narratives plays a lesser but still significant role as an amplifier in the causal chain between experience, trust, perception, and action.
- Communication must relate to risk perception. Four aspects of risk perception can be discerned that significantly impact risk communication (Renn and Benighaus 2013). This makes it evident that there will not be a "one size fits all" communication strategy. These aspects include (1) cultural background, including the

questions mentioned above of identity and meaning; (2) social-political factors, such as trust and personal values; (3) cognitive-affective factors, such as reference knowledge or prior beliefs; and finally, (4) heuristics of information processes, such as the affect heuristic or dread risks.

- This highlights that both scope and persistence are required for a successful communication campaign, especially if it involves complex subject matter. Highlighting the risk of tobacco smoking was a success after 30 years, while we still have not found a successful approach to discuss the disposal of nuclear waste (Kasperson 2014). The scope is relevant, as a complex subject matter will affect a large group of stakeholders, most likely in different ways. Persistence is relevant, as a “slow thinking” engagement requires time, especially to reach a larger population group.
- Concerning the affect heuristic discussed above, a communication strategy that credibly establishes the benefits of a specific action will automatically reduce the perceived risk, and in reverse, a communication strategy that aims to maximise perceived risk will automatically discredit any possible benefits.
- The affect heuristic also has implications for more established technologies: As benefits are being taken for granted (e.g. mobile phones) and thus become less immediately apparent, the concern for potential risks (i.e. “5G radiation”) increases.
- Risk communication involving low probability but high consequence events is difficult, as other risk perception factors play a significant role. This includes dread risk (based on novelty and degree of perceived control over the risk) and the resulting social amplification of risk. The resulting implications for risk communication are: if novelty and lack of control are emphasised, the risk will be communicated as much more substantial (and vice versa).
- It remains a fact that decision-makers are not particularly interested in detailed risk- and uncertainty-based assessments. There is a natural conflict of interest that encourages decision-makers to find “hard evidence” supporting their actions to minimise their liability in case of negative outcomes. Risk communication is not just a challenge for the general public.

Social movement theory plays an essential role in linking public engagement and risk communication to action, especially public action. When contemplating large engineering systems interventions, public support (or opposition) is crucial. Arguably, the objective of engagement and communication is to incentivise constructive actions and disincentivise destructive action. Social movement theory offers an explanatory framework for when and why people move from being complacent to taking collective action. Work on social movement theory in the context of large engineering projects has shown that three major factors are influencing public action (Scott et al. 2011):

- A perceived opportunity or threat. This may concern a wide range of values, such as power, civil liberties, money, or health. The relationship to risk communication is twofold: Either the public sees an opportunity to overcome a long-established perceived risk, or there is a perception of an emerging threat that must be countered.

- Mobilising structures: Mobilising structures include means of communications as well as creating opportunities for action. Risk communication, especially if it aims to amplify risk perception, profits from social amplification of risk, i.e. the tendency of an appealing story to turn "viral" in both traditional media and social media. To be effective, this must be accompanied by a concrete option for action – from a "like" to protest and boycotts.
- Framing of the narrative: The framing provides the "fuel" for action by fulfilling the affective requirement for emotions. The most effective drivers are fear and anger, creating an imbalance favouring the amplification of risk perception by exploiting perception biases. It also creates the collective identity of "us vs. them" necessary to incite action, further playing into the hands of those seeking to reduce the problem to a simple black-and-white storyline.

Understanding and Managing Uncertainty in Engineering Systems

Uncertainty Under Conditions of Commensurate Values

As engineering systems design tasks often include a high degree of technical novelty and design systems for very long life cycles with currently not precisely known operating environments or user needs, conditions of uncertainty are common where knowledge of probabilities is unavailable to designers.

The first commonly used method for dealing with uncertainty is through a Delphi (Linstone and Turoff 1975). The Delphi method derives its name from the ancient Greek oracle of Delphi, which rulers throughout ancient Greece consulted before any significant undertaking. The Delphi method is a well-established method for exploring uncertain futures developed in the mid-1950s at the RAND Corporation (Linstone and Turoff 1975). In essence, the Delphi method is a structured, iterative, and qualitative form of expert elicitation. A panel of experts is identified. Each of them is asked to fill out a survey. Next, the experts' answers are collected and synthesised, and a new survey is sent out. This new survey contains anonymised responses from the first round as selected by the people running the Delphi. Each expert can now update her answer as well as respond to any thoughts of the other experts. This second round of surveys is again analysed to see where experts are converging and where disagreements remain. By iterating in this way, over time, the method aims at arriving at a consensus among the panel of experts. Essential in performing a Delphi is to carefully structure the flow of information, have repeated feedback and updating of beliefs of experts in light of this, as well as ensure anonymity of the experts.

A second widespread way of dealing with uncertain futures is by scenario planning. The term "scenario" is derived from the movie and theatre world. It used to indicate the "course of events" or the "story in its context." Working at the RAND

Corporation, Herman Kahn started using the term scenario for his work on exploring the possible ways in which nuclear exchange with the Soviet Union might unfold (Bradfield et al. 2005). At the end of the 1960s and the beginning of the 1970s, the term scenario was also used in other areas. Known examples can be found in the reports to the Club of Rome, where exhaustion of the world's natural resources stock is sketched (Meadows et al. 1972, 2004), and in the energy scenarios that played a central role in the "Social Discussion Energy Policy" in the Netherlands at the beginning of the 1980s. In that discussion, scenarios were sketched in which, based on policy choices, an essential part of Dutch electricity would be generated through nuclear energy, coal, or reusable resources (sun, wind, and water). Scenarios are also used in the business sector. The most striking example of this is Shell. Thanks to the scenario Shell developed in the late 1960s and early 1970s, the company was better prepared than the competition for the unexpected changes in the oil market during the oil crisis that was precipitated by the OPEC in the 1970s (Chermack 2017).

During the last decennium, working with scenarios has become very popular in the private and public sectors. At the same time, the use of the term has widened considerably. The term "scenario" is so general that it can indicate every form of exploration of the future, including explorations based on extrapolations, regression models, or causal simulation models. For example, in international climate research, they speak of diverging climate scenarios resulting from "high" or "low" emission scenarios. The term is also used in other disciplines, such as safety science. There it involves the possible combinations of disrupting circumstances that cause failures. The consequence is that we cannot speak of "the" scenario approach. Approaches vary widely, where the terms "scenario" and "scenario approach" are used differently.

This variety of ways in which the term scenario is being used can be structured by considering three different dimensions (Enserink et al. 2010). These dimensions are:

- **Time**: a scenario describes either an uncertain future at a certain point in time or the dynamics over time from the present situation to a future one.
- **Values**: some scenarios are explicitly normative, describing, for example, an ideal future utopia or a dystopia. Other scenarios instead remain silent on the desirability of the described events and offer an exploration of what might or could (but not should) happen. Explorative scenarios are often used to stress test candidate strategies on their robustness, while normative scenarios are often used as a starting point for discussing how we might arrive at that desired future.
- **Scope**: scenarios can differ in what aspects of a problem or system are considered. A context scenario describes a possible external context of a policy problem. A policy scenario described what the implementation of a given policy might look like. A strategic scenario describes both context and policy.

Many methods exist for creating scenarios. These methods can be grouped into different families, depending on their origin. Arguably the best-known family of methods is known as scenario logic. Scenario logic methods are typically used for creating context scenarios. It typically starts with identifying critical exogenous forces affecting the system under investigation. Next, these forces or factors are grouped based on relatedness. These groups are sometimes also known as megatrends. The various megatrends are evaluated regarding how uncertain their future evolution is and how significant their impact on the system is. The aim is to identify the two or three critical megatrends that are highly uncertain and strongly affect the system. These two or three megatrends form a scenario logic. Given two megatrends, you have four scenarios by taking the extreme ends of both megatrends. Given three megatrends, you have eight possible scenarios. Typically, not all eight would be fully developed. Instead, analysts are encouraged to pick the non-trivial, more surprising combinations and develop these into fully fledged scenario narratives. This is motivated by the fact that scenario analysis aims to engage in a strategic conversation. Best case, worst case, and business as usual scenarios are at the forefront of everyone's mind, so these do not tend to foster a strategic conversation.

Uncertainty Under Conditions of Incommensurate Values

The conditions of uncertainty in engineering systems design extent to conditions where in addition to the absence of probability data, there is also a lack of agreement, or at least significant ambiguity, regarding the alignment of critical stakeholder values. As engineering systems design challenges involve large stakeholder groups, this situation is not unusual and has been explicitly addressed in situations requiring long-term policy decisions governing engineering systems design.

In recent years, primarily in the context of climate adaptation and climate mitigation, there has been a growing interest in developing and testing new approaches for supporting multi-stakeholder decision-making under uncertainty. Typically, in these contexts, the various parties to a decision do not agree on which outcomes matter and their relative importance. Moreover, they do not know what the future will look like and might have profoundly different ideas about this. This combination of value incommensurability and Knightian uncertainty is also called "deep uncertainty." Under the label of decision-making under deep uncertainty, various approaches have been put forward.

What unites the various approaches for supporting robust decision-making under deep uncertainty is three key ideas:

1. **Exploratory scenario thinking**: In the face of deep uncertainty, one should explore the consequences of the various presently irreducible uncertainties for decision-making. Typically, in the case of complex systems, this involves the use of computational scenario approaches. The use of models is justified by the observation that mental simulations of complex systems are challenging to the point of infeasibility (Sterman 1989; Brehmer 1992).
2. **Adaptive planning**: Adaptive planning means that plans are designed from the outset to be adapted over time in response to how the future may unfold. The way a plan is designed to adapt in the face of potential changes in conditions is

announced simultaneously with the plan itself rather than in an ad hoc manner post facto.

3. **Decision aiding**: Decision-making on complex and uncertain systems generally involves multiple actors agreeing. In such a situation, decision-making requires an iterative approach that facilitates learning across alternative framings of the problem and learning about stakeholder preferences and trade-offs in a collaborative process of discovering what is possible (Herman et al. 2015). In this iterative approach, the various decision-making approaches under deep uncertainty often put candidate policy decisions into the analysis by stress testing them over a wide range of uncertainties. Their effect on the decision then characterises the uncertainties. The challenges inherent in such processes are reviewed in depth by Tsoukiàs (2008).

The various approaches for decision-making under deep uncertainty all follow essentially the same stepwise approach. One starts with the identification of promising decision alternatives. This can be based on expert opinion, but often it involves the use of (many-objective) optimisation. The aim is to find solutions that collectively represent the trade-offs across the various incommensurable objectives. Next, these solutions are evaluated across many different scenarios. These scenarios represent alternative ways in which the various uncertain factors might play out in the future. The results of this evaluation are analysed in the next step using various machine learning algorithms. The aim is to partition the space spanned by the various uncertain factors into regions where policies can satisfy pre-specified minimum performance requirements and regions where policies fail to do so. Ideally, these regions are characterised by human interpretable rules. Next, the analyst faces a choice. If the regions of failure are judged to be significant, a second iteration starts. New or modified policies that are expected to be less vulnerable are put forward, stress-tested, and analysed. This iterative process continues until a set of solutions emerges that is judged to perform satisfactorily across the entire uncertainty space. Once such a set is found, the final step is to analyse the trade-offs on the various objectives under uncertainty.

Central in decision-making under uncertainty is the idea that decisions and the resulting engineering systems interventions and governing policies should be robust. A wide and varied literature exists on how to measure robustness. A significant distinction is between robustness as being able to perform satisfactorily in many scenarios and robustness as not regretting the choice. A well-known and often used satisficing robustness metric is the domain criterion. The domain criterion measures the fraction of scenarios in which a given policy option can meet pre-specified performance constraints. In the outlined approach to supporting decision-making under deep uncertainty, this domain criterion is implicitly used to partition the uncertainty space into regions of success and failure. Satisficing metrics focus on each policy option.

In contrast, regret metrics are comparative. A well-known regret metric is minimax regret. This metric first assesses for each scenario what the best performance is. Next, for each policy option, one calculates the difference between the best possible performance and the performance obtained by the option under consideration. The most robust (or least regret) option has the lowest maximum regret across all scenarios. Since satisficing and regret metrics measure different dimensions of what it means for a policy option to be robust, it is good practice to use both.

Understanding and Managing Ignorance in Engineering Systems

Ignorance in engineering systems design implies that we are unaware of, for example, critical requirements, technical limitations, or future operating scenarios. Given the long life cycles of engineering systems and the diverse stakeholder base during their design and operation, addressing "ignorance" during engineering systems design and later construction and operation is critical. This implies embracing the fact that engineering systems design is never finished but requires ongoing attention during construction and operation as new knowledge emerges – or at the very least, evidence of the absence of critical knowledge.

There is a continuum of management practices to address conditions of ignorance during the design, construction, and operation of engineering systems. The particular challenge is here, again, to address both technical and social factors – be it as "sources" of ignorance or as impact areas of ignorance. In the following sections, we will discuss the associated capabilities under the umbrella term of resilience.

We define resilience as an engineering system's capability to provide critical functions under conditions of unforeseen change, i.e. responding to the effects of ignorance. For a discussion of the history of resilience thinking and a review of a range of definitions, please see Alexander (2013), Rose (2017), and Wied et al. (2020).

Following Holling's original thinking on ecological resilience, there are two related key aspects in resilience management (Holling 1973, p. 21): First, resilience management addresses recognised ignorance. It is based on the assumption that future events are not foreseen and practically not foreseeable in their diversity. In practical terms, resilience management starts where a carefully crafted risk register ends – resilience management expects the unexpected. The second aspect is that, consequently, resilience management emphasises general preparedness to respond to a surprising future instead of specialised capabilities to respond to particular events.

To operationalise resilience in a specific context, we need to answer three questions (Wied et al. 2020b).

1) Resilience of what? What are the key performance attributes of the engineering systems that are the focus of attention? Performance attributes may be critical functions, such as a certain level of communication capability or food supply. They may also be indirectly expressed through protecting the integrity of specific system elements (e.g. protecting an institution or community) or system relationships (e.g. maintaining control).
2) Resilience to what? Ideally, resilience provided general preparedness for any unforeseen changes: sudden or gradual, temporary or permanent, internal or

external, technical or social, affecting any element and possible combination of the engineering systems. In practical terms, there must be scoping decisions, leading to a not-quite-general preparedness.

3) Resilience how? The bulk of this section deals with resilience management practices for engineering systems. They address both structural factors (i.e. the configuration of the engineering systems with its elements and relationships) and dynamic factors of system behaviour and governance.

Commensurate with the range of definitions of resilience (see above), there are various conceptualisations of resilience response timelines. Figure 3 summarises several resilience-related properties of engineering systems:

- Preparedness describes the degree to which an engineering systems can be considered "generally prepared" to face unexpected, adverse changes.
- Robustness describes the capability of an engineering systems to continue providing critical function at a practically nominal rate while being impacted by unexpected changes.
- Resistance expresses capabilities to affect a graceful degradation of functionality that is both slow and able to maintain critical levels.
- Recoverability summarises the engineering systems capability to recover from short-term disruptions and/or adapt to permanent changes.
- Antifragility expresses the concept that engineering systems can improve by exposure to unforeseen changes and achieving a performance exceeding pre-disturbance levels.

The following two sub-sections introduce resilience models and practices that are relevant in the context of engineering systems. We consider approaches relating to both socio-organisational resilience (project resilience, organisational and organisational network resilience, team and individual resilience) and technical

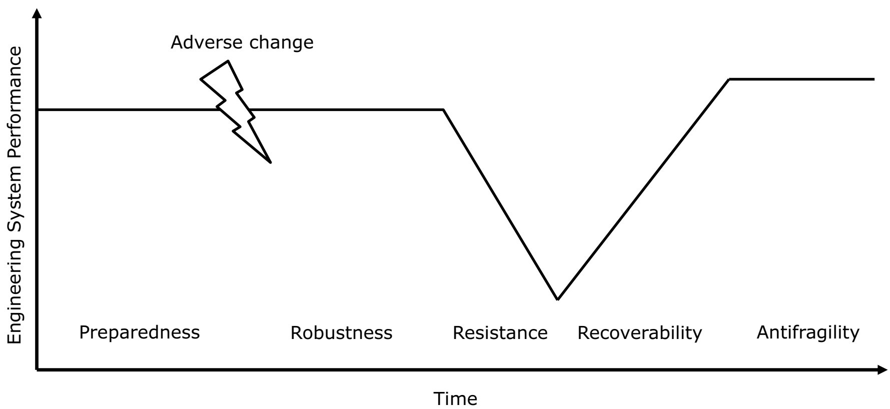

Fig. 3 Resilience-related properties of engineering systems

and engineering resilience approaches as dealing with ignorance under conditions of commensurate values: Performance attributes are typically clearly articulated and agreed upon. In the second section, we consider resilience approaches that cover conditions of incommensurate or unknown values, such as socioecological approaches to resilience and the application of the precautionary principle.

Ignorance Under Conditions of Commensurate Values

Technical and engineering resilience: From an engineering perspective, resilience is an emergent system property that mitigates between uncertain conditions and system performance (Jackson and Ferris 2013; Uday and Marais 2015; Wied et al. 2020b). Typical related properties are summarised in Table 4. It has been studied in the context of systems engineering, alongside other related emergent properties such as survivability (Ellison et al. 1999), changeability (Ross et al. 2008), flexibility (Broniatowski 2017; Ryan et al. 2013), or robustness (Potts et al. 2020; Ross et al. 2008). The focus is on maintaining defined functions, avoiding discontinuities, and rapidly recovering functionality to a pre-disruption state. In the safety community, the concept of "resilience engineering" (Hollnagel et al. 2006; Leveson 2020; Aven 2022) has emerged.

Socio-organisational resilience: While any structuring will somewhat remain arbitrary, we will discuss socio-organisational resilience into three categories: (1) Individual and team resilience; (2) project and organisational resilience; and (3) supply chain and industry resilience (see Table 5).

Individual and team resilience directly impact overall engineering systems resilience, as human action and decision-making (or non-action and non-decision-

Table 4 Resilience as an emergent property (following Wied et al. 2020b)

Category of resilience properties	Emergent resilience properties
Recovery	Recover, return, self-righting, reconstruction, bounce back, restore, resume, rebuild, re-establish, repair, remedy
Absorption	Absorb, tolerate, resist, sustain, withstand, endure, counteract
Adaptation	Adapt, reorganise, transform, adjust, re-engineer, change, flexibility, self-renewal, innovation
Reaction	Respond, react, alertness, recognition, awareness
Improvement	Improve, grow
Prevention	Prevent, avoid, circumvent
Minimal/graceful deterioration	Minimal, restricted, acceptable, contained, graceful deterioration/degradation
Anticipation	Anticipate, predict, plan, prepare
Coping	Coping, cope
Survival	Survival, persistence
Mitigation	Mitigation, manage consequences
Others	Learning, management, action, resourcefulness

Table 5 Overview of socio-organisational concepts of resilience

Area of socio-organisational resilience	Key aspects
Individual and team resilience	Critical review of the concept of individual psychological resilience (Fletcher and Sarkar 2013) Factors shaping individual resilience to high-stress environments (Rees et al. 2015) Review of "team resilience" concepts in workplace context (Chapman et al. 2020) and empirical study of influencing factors (Alliger et al. 2015) Relationship of individual psychological resilience and organisational incentives (Shin et al. 2012) Describing and enhancing resilience of small groups (Zemba et al. 2019)
Resilience of temporary (i.e. projects) and permanent organisations	Theory and practice of resilience in project management (Kutsch et al. 2015; Wied et al. 2020b) Organisational capabilities enabling recovery and disaster response (Chang-Richards et al. 2017; Choi et al. 2019; Steinfort 2017), including business continuity (Herbane et al. 2004; Hiles 2010) Review of "organisational resilience" concepts, theoretical framing, and quantification approaches (Barin Cruz et al. 2016; Burnard and Bhamra 2011; Duchek 2020; Linnenluecke 2017; Vogus and Sutcliffe 2007; Wood et al. 2019)
Supply chain and enterprise resilience	Concepts and application of supply chain resilience (Bhamra et al. 2011; Brusset and Teller 2017; Kamalahmadi and Parast 2016; Sheffi 2017) Resilience of extended enterprises and industries (Erol et al. 2010; Sheffi 2005)

making) are vital to any sociotechnical system. Resilience, as a psychological concept on the individual and group level, most commonly describes the ability of individuals and groups to maintain performance under extraordinary circumstances and learn from those experiences.

The organisational level focuses on capabilities, practices, and organisational structures that relate larger groups of individuals with one another and their technical infrastructure within permanent and temporary organisations. Research in this domain addresses both generic resilience capabilities, practices, and theories and contains a significant body of work explicitly dedicated to response and recovery activities. Both project and organisational perspectives on resilience are highly relevant in the engineering systems context, as they form integral parts of the operation of and intervention in engineering systems.

Supply chain and enterprise resilience: The most comprehensive level of socio-organisational resilience in engineering systems is the resilience of extended supply chains and enterprises. They can be seen as the overall possible "organisational solution space" to operate and change engineering systems. Resilience concepts here focus both on currently implemented supply chains and enterprise architectures and their possible alternative configuration, including the reconfiguration of existing partners and adding/removing stakeholders.

Ignorance Under Conditions of Incommensurate Values

The concept of "incommensurate values" becomes problematic in the context of ignorance and resilience, as resilience by definition does not rely on foresight. However, in practical terms, resilience does require us to explicitly articulate the resilience "of what" and "to what." While not necessarily representing incommensurate values, we will in the following discuss concepts of "general resilience" that do not necessarily expect an articulation of specific common resilience targets.

The resilience discussion is typically placed in the context of "social-ecological systems," as the primary source of adverse events that is studied are "unprecedented disturbances" from natural disasters and their knock-on effects, resulting in "unfamiliar, unexpected and extreme shocks" (Carpenter et al. 2012). They discuss system-level properties that partially overlap with those discussed for technical or engineering resilience, such as diversity, modularity, openness, reserves, feedbacks, nestedness, monitoring, leadership, and trust.

In social-ecological systems theory, resilience is an integral part of the dynamics and development of those systems, alongside adaptability and transformability (Folke et al. 2010). In this context, adaptability describes the system's capability to continually "adapt" to changing external stimuli to stay within critical performance thresholds, while transformability refers to the capability of the system to transcend those thresholds into new development paths. A vital attribute here is nestedness, i.e. the capability of learning on the subsystem level from more minor disturbances to create system-level resilience capabilities. A central argument thus becomes that we must focus on smaller-scale resilience to enable larger-scale resilience that may be too complex to influence directly.

A significant area of research is the relationship between system-level resilience and sustainability. This is a two-way relationship, as humans both shape the biosphere and are in turn shaped by it (Folke et al. 2016). In this context, sustainability is an enabler of long-term resilience and the lack of sustainability becoming a driving need for additional resilience. The governance of sociotechnical transitions in the context of social-ecological resilience is one key area (Smith and Stirling 2010; Wilkinson 2012).

Attempts to further characterise "general resilience" through taxonomies yield similar characterisations as those of specific resilience discussed previously (Maruyama et al. 2014), i.e. type of shocks, target systems, time-phase of concern, and type of recovery, while still attempting to identify higher-order resilience principles such as redundancy, diversity, and adaptability.

Other aspects of general resilience include social-ecological memory and how diversity in those memories is relevant to foster general resilience (Nykvist and Von Heland 2014).

A specific focus in the context of resilience provides the school of thought surrounding the precautionary principle. While the precautionary principle is discussed in a context that does not necessarily use the term "resilience," the objective is similar: protecting sociotechnical, or social-environmental, systems from harm in the face of ignorance as well as uncertainty (Sandin et al. 2002).

However, the precautionary principle does imply that action is mandatory in order to protect health and the environment (Sandin 1999) and has an explicit legal (Sunstein 2003) and ethical (Manson 2002) dimension. The precautionary principle has become a central element of national and international policy making (Foster et al. 2000; Kriebel et al. 2001), while the expected "standard of proof" necessary to justify action remains debated.

The "standard of proof" debate highlights an interesting tension: The tension between the "need for certainty to take action" and the "need to take action under uncertainty." It pervades all types of management and decision-making under conditions of risk, uncertainty, and ignorance.

Conclusion

We believe that effectively engaging – and leveraging – uncertainty in all its facets is a critical success factor in engineering systems design. In this chapter, we introduced a more nuanced interpretation of the term "risk management" that, we believe, does justice to the complexity of engineering systems design tasks. By decomposing "risk" along levels of increasing uncertainty into risk, uncertainty, and ignorance, we enable a more goal-oriented development, discussion, and use of "risk management practices" that fit their specific purpose. As complex stakeholder landscapes also characterise engineering systems design tasks, we further differentiate our practices for commensurate and incommensurate stakeholder values.

"Classic" techniques of risk management must further evolve to fully address emergent risk phenomena in cyber-physical-social systems, including, for example, risks associated with the performance, validation, and trust in AI-based systems. The applications of uncertainty management must further grow into the mainstream of early engineering systems design activities, supporting a broader exploration of solution alternatives and enabling a more meaningful early-stake stakeholder dialogue to build trust and legitimacy. With the large engineering systems level interventions necessary to make the sustainable transformation of our critical infrastructure a reality, our design approaches also need to be able to handle the uncertainty inherent in future climate developments. And finally, we must embrace resilience as a core design objective, both in terms of achieving technical resilience and supporting societal resilience, and thus cohesion, through engineering systems design.

Cross-References

- ► Designing for Emergent Safety in Engineering Systems
- ► Engineering Systems Design: A Look to the Future
- ► Engineering Systems Integration, Testing, and Validation
- ► Engineering Systems Interventions in Practice: Cases from Healthcare and Transport

► Flexibility and Real Options in Engineering Systems Design
► Properties of Engineering Systems
► Technical and Social Complexity
► The Evolution of Complex Engineering Systems

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Properties of Engineering Systems

11

Donna H. Rhodes and Adam M. Ross

Contents

D. H. Rhodes (✉) · A. M. Ross
Sociotechnical Systems Research Center, Massachusetts Institute of Technology, Cambridge, MA, USA
e-mail: rhodes@mit.edu; adamross@mit.edu

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Abstract

Engineering systems are complex socio-technical systems that serve societal needs, existing over long lifespans during which they continue to evolve. This chapter focuses specially on desired engineering system properties and their relevance to designing effective interventions that ultimately result in sustainable value delivery to society. Desired properties, as discussed in this chapter, are higher-order properties, emerging as a consequence of the intersection of challenges, decisions, and design interventions put in place. They enable responding to the broad challenges that engineering systems face, including life cycle, complexity, human behavior, uncertainties, and dynamics. This chapter describes the characterization of engineering system properties, sometimes referred to as *ilities* or nonfunctional requirements. Considerations for pursuing desired properties and the approach for their pursuit are discussed. Design principles serve as prescriptions for specific design interventions that enable the design and evolution of an engineering system that possesses the desirable system properties over its lifespan.

Keywords

Design principles · Engineering systems · Engineering systems design · Ilities · Nonfunctional requirements · System properties

Introduction to Properties of Engineering Systems

This chapter provides a brief overview of engineering systems as relevant to the discussion of engineering system properties. Part I of the *Handbook of Engineering System Design* discussed the engineering systems perspective. In this second part of the handbook, engineering systems are described. The subject of this chapter is properties of engineering systems as responses to challenges faced by engineering systems. This chapter discusses the characterization of engineering system properties, including several alternative approaches. Considerations and approaches for pursuit of engineering system properties are examined, and design principles are introduced as prescriptions that inform the design of engineering system interventions. This first section in the chapter briefly describes engineering systems and discusses the importance of designing for engineering system properties.

What Are Engineering Systems and Why Are They Important?

Engineering systems, such as a multi-modal transportation system, are complex socio-technical systems, involving dynamic social and natural interactions with technology. Initially, an engineering system comes about through originating intent that drives an initial system architecture. Comprised of many constituent systems, products, and services, these systems continuously evolve over a long lifespan.

Engineering systems properties such as resilience, flexibility, and sustainability "result from the collective structure and behaviour of the various technological, human, and natural components and subsystems that are woven together in complex ways" (de Weck et al. 2012). Challenges to the success of engineering systems arise from these complexities and sustainment of value delivery to stakeholders, as their preferences shift with experiencing the system in the context of a changing ecosystem over a potentially long lifespan.

Engineering system properties provide the means to articulate design goals and evaluation criteria that can then be realized through design interventions. These interventions are seldom purely technical or purely social, but instead are socio-technical in nature. For instance, a new technology may improve system performance but may also necessitate policy change and new strategies to foster stakeholder acceptance. This underscores the need for designers to have a deep understanding of engineering system properties and the respective design principles that will enable purposeful design interventions. The design of interventions itself is a complex process that requires trade-offs, considering both technical and social dimensions. Interventions do not result in instantaneous change but rather create the circumstances for movement in the desired direction.

Chapter Outline

Section "Overview of Engineering System Properties and Their Relevance" introduces engineering system properties and discusses them relative to the motivating challenges described in prior chapters of Part II of the handbook. This section discusses the importance of capturing a comprehensive description of engineering systems properties. Properties are discussed as providing a means to articulate design goals and associated evaluation criteria. Section "Engineering System Properties as Responses to Challenges" discusses engineering system properties as responses to address five broad challenges that engineering systems face: life cycle, complexity, human behavior, uncertainties, and dynamics. Several examples of how properties provide responses to the challenges are briefly described. Section "Approaches for Characterizing Engineering System Properties" begins with a discussion on what comprises a good property. Four approaches to characterizing engineering system properties are presented, including declared text-based definitions and visual representations, classification approaches, formal description using a semantic basis, and quantitative measures. The section describes thinking through and specifying engineering system properties, so that they eventually can be assessed and verified. Section "Considerations for Pursuing Engineering System Properties" discusses considerations for the pursuit of desired engineering systems properties, demonstrating complexities that are involved. Considerations discussed include constraints and influences of the external environment, extent of a property across the engineering system, interrelationship and dependencies, and trade-off between properties. Section "Approaches to Pursuing Engineering System Properties" provides insight into approaches for the pursuit of desired properties in two cases. The first is designing for intended properties given anticipated emergent needs. The second case is pursuing system properties to enable the capacity to respond to unanticipated emergent needs. The section also discusses design principles for designing interventions for intended system properties.

Overview of Engineering System Properties and Their Relevance

This section overviews what is meant by engineering system properties. It highlights the focus of the chapter on desired engineering system properties relative to the motivating challenges described in prior chapters of Part II of the handbook. The motivation and importance of capturing a comprehensive description of engineering systems properties is described. Properties are discussed as providing a means to articulate design goals and associated evaluation criteria.

Describing Engineering System Properties

Descriptions of engineering system properties are a function of the system of interest, the describer, state of current knowledge on this property, and formality with which a description is composed. Point of view matters. Desired properties, as discussed in this chapter, are higher-order properties, emerging as a consequence of the intersection of challenges, decisions, and design interventions put in place.

Engineering system properties are sometimes referred to as nonfunctional requirements (NFRs). While NFRs such as reliability and quality are traditional properties in products and systems, this chapter focuses on selected engineering system properties that provide emergent value in engineering systems. The term *ilities* is often used in the literature defined as a *nonfunctional requirement* or a property of a system, product, or service. More recently, the term *system quality attribute* has been used in the systems literature (Boehm and Kukreja 2015). For the purposes of this chapter, unless otherwise specified, any use of the term *ilities* is used to mean an *engineering system property.*

There are many ways to describe engineering systems properties, from expert-opinion text definitions as the most ad hoc and quantitative measures as the most structured. Section "Approaches for Characterizing Engineering System Properties" of this chapter will discuss several approaches for characterizing properties. In describing engineering system properties, it is important to understand that subjectivity is involved. Describing properties is challenging as generally the resulting description reflects the describing individual's preferences and biases. Additionally, descriptions are somewhat influenced by the domain (e.g., transportation, energy) and discipline (e.g., systems engineering, software, safety). The descriptions of properties may also be a function of the knowledge existing about that property at the time it was articulated.

What Are Engineering System Properties?

A *property* is an attribute, quality, or characteristic of something (Oxford Languages). There are many properties that an engineering system can be said to possess. Four properties that have been widely recognized in traditional engineering are quality, safety, usability/operability, and maintainability/reliability. These properties and many others are discussed throughout other chapters in the handbook. Broadly speaking, Lee and Collins (2017) position system properties (a.k.a. *ilities*) as "desirable and anticipated emergence of a system. In a similar manner, the negation of *ilities* is also defined to be an emergent property of a system." For engineering systems, it is important to design for desired properties and, when doing so, consider possible perturbations that could result in degraded value. *Desired engineering system properties*, as we discuss in this chapter, are desirable emergent properties of increasing importance to modern socio-technical systems.

Engineering systems necessitate consideration of a much-expanded set of properties. According to de Weck et al. (2011), desired properties of systems, such as flexibility or maintainability, often manifest themselves after a system is placed into initial use. They state, "These properties are not the primary functional requirements of a system's performance, but typically concern wider system impacts with respect to time and stakeholders than are embodied in those primary functional requirements" (de Weck et al. 2011). This chapter focuses specially on *desired engineering system properties* and their relevance to designing effective interventions that ultimately result in sustainable value delivery to society. Three desired properties for the engineering system at large are those often described using the terms *resilience*, *evolvability*, and *adaptive capacity*. These higher-order properties are achieved through other enabling properties, such as those relating to system structure and behavior (e.g., modularity, scalability). It is important, though, to realize that there is no generalized hierarchy of properties.

The set of possible desirable engineering system properties is virtually endless. Table 1 lists 230 selected system properties that represent the combination of many different authors' literature surveys (e.g., Chung et al. 2000; ESD 2001; Mairiza et al. 2010; INCOSE 2015; Adams 2015). The list is not exhaustive and continually grows as new concepts are born and old ones diverge into subtle variations.

Table 1 Example list of potential engineering system properties

Accessibility	Comprehensibility	Distributivity	Immunity	Operability	Replicability	Surety
Accountability	Comprehensiveness	Diversity	Impact analyzability	Operating cost	Reproducibility	Survivability
Accuracy	Conceptuality	Domain analysis cost	Independence	Peak-period performance	Resilience	Susceptibility
Adaptability	Conciseness	Domain analysis time	Informativeness	Performability	Response time	Sustainability
Additivity	Confidentiality	Durability	Inspection cost	Performance	Responsiveness	System Effectiveness
Adjustability	Configurability	Effectiveness	Inspection time	Planning cost	Retirement cost	Tailorability
Affordability	Conformance	Efficiency	Installability	Planning time	Reusability	Testability
Agility	Consistency	Elasticity	Integratability	Plasticity	Risk analysis cost	Testing time
Analyzability	Contractability	EM Compatibility	Integrity	Portability	Risk analysis time	Throughput
Anonymity	Controllability	Enhanceability	Interchangeability	Precision	Robustness	Time performance
Atomicity	Coordination cost	Environmental Impact	Internal consistency	Predictability	Safety	Timeliness
Attractiveness	Coordination time	Evolvability	Interoperability	Privacy	Scalability	Tolerance
Auditability	Correctness	Exchangeability	Intuitiveness	Process management time	Secondary-storage performance	Total Cost of Ownership
Augmentability	Cost	Execution cost	Learnability	Producibility	Securability	Traceability
Availability	Cost Effectiveness	Expandability	Legibility	Productivity	Security	Trainability
Buffer space performance	Coupling	Expressiveness	Likeability	Project stability	Self-descriptiveness	Transferability
Capability	Customer evaluation time	Extendability	Localizability	Project tracking cost	Self-repairability	Transparency
Capacity	Customer loyalty	Extensibility	Main-memory performance	Promptness	Sensitivity	Trustability

Certainty	Customizability	External consistency	Maintainability	Prototyping cost	Serviceability	Ubiquity
Changeability	Data-space performance	Fail-safe	Maintenance cost	Prototyping time	Similarity	Understandability
Clarity	Debuggability	Fault-tolerance	Maintenance time	Provability	Simplicity	Uniform performance
Code-space performance	Decomposability	Feasibility	Manageability	Quality	Software cost	Uniformity
Cohesiveness	Defensibility	Fidelity	Manufacturability	Quality of service	Software production time	Usability
Commonality	Degradability	Flexibility	Maturity	Reactivity	Space boundedness	User-friendliness
Communication cost	Degradation of service	Formality	Mean performance	Readability	Space performance	Validity
Communication time	Demonstrability	Functionality	Measurability	Reconfigurability	Specificity	Variability
Communicativeness	Dependability	Generality	Mobility	Recoverability	Stability	Verifiability
Compatibility	Deployability	Graceful Degradation	Modifiability	Recovery	Standardizability	Versatility
Completeness	Determinability	Guidance	Modularity	Reengineering cost	Structuredness	Viability
Complexity	Development cost	Habitability	Naturalness	Reliability	Subjectivity	Visibility
Component integration cost	Development time	Hardware cost	Nomadicity	Repairability	Substitutability	Vulnerability
Component integration time	Disposability	Heterogeneity	Observability	Repeatability	Suitability	Wrappability
Composability	Distributability	Homogeneity	Off-peak period performance	Replaceability	Supportability	

Engineering System Properties as Responses to Challenges

This section discusses engineering system properties as responses to address the broad challenges that engineering systems face. Five types of challenges highlighted are life cycle, complexity, human behavior, uncertainties, and dynamics. These five challenges and many others are discussed by various authors throughout the handbook in more detail. In this chapter, discussion focuses on the context of how engineering system properties provide responses toward addressing such challenges. Several examples of how system properties provide responses to the challenges are briefly described.

Properties That Enable Engineering Systems to Address Broad Challenges

Since engineering systems have a potential for long lives and broad socio-technical scope, they face a much larger set of possible challenges over their effective lifetime than traditional systems. Meeting functional requirements, and even traditional nonfunctional requirements such as *reliability*, *maintainability*, and *availability*, is not sufficient to be perceived successful. Instead, engineering systems must exhibit a set of properties that enable them to manage the broad set of challenges. These challenges reflect a myriad of intersections between engineering systems and their environment, human experience, and time. Specifically, desirable properties of engineering systems enable appropriately addressing challenges that arise due to life cycle, complexity, human behavior, uncertainty, and dynamics. Such properties include a broad set of qualities that reflect how an engineering system might respond (e.g., agile or adaptable), or not need to respond (e.g., robust or versatile), to these challenges. The next sections briefly describe these challenges in more detail.

Challenge #1: Life Cycle

Given that engineering systems typically exist over a long period of time, it is natural to expect certain properties of an engineering system to address that time span. Whether the engineering system has a classical "life cycle" of conception through implementation and operation until retirement and disposal, or a modern emergent and evolving existence, qualities that address how the system is experienced over time may be warranted. As an example, the total cost of a system, in both monetary and nonmonetary terms, may be important. Achieving appropriate cost relative to other costs experienced by a system owner or operator fundamentally relate to the perceived affordability of the engineering system. The concept of *affordability* means little without the time element and thus can only really be considered over the lifespan of a system. Similarly, the ability for the engineering system to continually provide capability at an acceptable level of resources, whether it be constant or at least predictable, relates fundamentally to the property of sustainability. Sustainable systems are those that can maintain performance at cost over a long period of time.

Challenge #2: Complexity

One of the key accepted, perhaps even expected, aspects of an engineering system is its inevitable intersection with the concept of complexity. de Weck et al. (2011) describe a system as "behaviourally complex if its behaviour is difficult to predict and structurally complex if the number of parts is large and the interconnections between its parts is intricate or hard to describe briefly." Dodder and Sussman (2002) use the term "nested complexity" to describe an engineering system as being a physical system embedded in a policy system, where the physical system is being "managed" by a complex organizational and policymaking system. Sussman (2003) describes evaluative complexity related to human behavior, where different engineering systems stakeholders each have their own views about good system performance. Rhodes and Ross (2010) define five aspects of complexity of an engineering system, including structural, behavioral, contextual, perceptual, and temporal. Each of these suggests a multitude of interactions and interrelated elements across a variety of domains, some of which may necessarily result in unpredictable, uncontrollable, or emergent phenomena in the engineering system. Myriad approaches have been developed in order to contain, or at least help to manage, the consequences of complexity. In the structural space, isolation of complexity into loosely coupled (i.e., "less interrelated and therefore less complex") elements is the essence of the property of modularity. Using *modularity*, one structures a system into a set of modules that, while perhaps tightly coupled within, hide that large number of interactions via a smaller set of relationships between modules. In this way, the apparent complexity of the system is reduced by abstracting elements to the module level.

Challenge #3: Human Behavior

As socio-technical systems, engineering systems exist to provide a societal need and fundamentally require humans for their development, operation, and maintenance. As such, judgment, even what might be considered "irrational" judgment, will influence how the system is experienced. The subjective experience of the system may impact its success. For example, an aesthetically pleasing train station, while itself a complex operating technical system, also generates positive feelings in its users, perhaps termed happiness. Variation in stakeholder behavior and their interaction with the engineering system may emerge over time in response to changing context (Rhodes 2018). A desirable emergent system property, such as trust, can be influenced to some degree by cultural beliefs (e.g., confidence in government-owned systems) and exogenous influences (national security risk assessment level). Due to the roles that humans play both "in" engineering systems and "on" engineering systems, with all of their associated strengths and limitations, means the scope of consideration for engineering system properties might need to include safety, usability, fail-safe, security, and understandability, among others.

Challenge #4: Uncertainty

Inevitably, there will be factors that impact an engineering system that cannot be predicted with complete accuracy. Examples of such factors may include the level of market demand for a telecommunication system, the stringency of emission standards for industrial power generation in 2030, or the price of oil that directly impacts the value of offshore drilling operations. For complex system of systems, degrees of operational independence of the constituent systems result in an endogenous uncertainty around how it might perform, not only because of emergent behaviors but also because the systems may decide to operate differently than intended. Both exogenous (outside of the system boundary) and endogenous (inside of the system boundary) uncertainties may impact the success of an engineering system. Given there may be unknown or uncontrollable factors that may impact success, some desirable system properties enable a system to be insensitive to (*robustness*) or be changed in response to (*flexibility*) such uncertainties. The pursuit of robustness can occur at any level of abstraction of the system, from components to subsystems to systems and its architecture. Fundamentally, the concept of robustness describes an insensitive relationship between some variation in inputs to some variations in outputs. As such, robustness describes a relative property (i.e., a system can be robust in {outputs of interest} to variations in {inputs of concern}). For example, a car may be robust in fuel efficiency to variations in driving conditions. Flexibility, on the other hand, describes the ease by which a system can be intentionally changed. The "ease" of making such changes can relate to monetary or non-monetary costs, such as effort or time expended. Conceptually, having flexibility then gives an engineering system an ability to respond to uncertainty in a way that allows it to continue to be valuable (de Neufville and Scholtes 2011).

Challenge #5: Dynamics

While the concept of "time" is inherent in the life cycle, complexity, and uncertainty challenges above, the ability to address changes due to time, at various timescales, warrants its own challenge category. Various timescales of need and response may be experienced at different points in the lifespan of an engineering system. This can reflect a need to accommodate environmental fluctuations on sub-second timescales (e.g., signal interference) to contextual variations that happen on multi-year timescales (e.g., national leadership change with associated legislative and regulatory agendas). A key factor that comes up again and again for successful systems is their ability to respond to variations on appropriate timescales. Short timescales in particular can stress a system, thereby reinforcing a need for *agility*, which is the ability of a system to respond nimbly to changes in a system environment. Being nimble can mean having the structures and policies in place to quickly account for changes via self-change or modification of behaviors in order to stay relevant in the face of new information or circumstances.

Approaches for Characterizing Engineering System Properties

This section discusses the different types of approaches to characterizing engineering system properties. It begins with describing what comprises a good property description. Four approaches for the characterization are discussed, including declared text-based definitions and visual representations, classification approaches, formal description, and quantitative measures.

What Comprises a Good Property Description?

Engineering system properties defy widely accepted and comprehensive definition, given the level of complexity and magnitude of the system and diversity of its stakeholders. Further, engineering system properties elude objective description given that the understanding of this property by any one individual is biased by their interests and background, as well as the circumstances under which it is examined. As a result, a proliferation of textual definitions exists for any given engineering system property. Wied et al. (2020) performed an analysis of the resilience literature that found 251 different definitions of the term *resilience*. Similarly, Ryan et al. (2013) found many different definitions of flexibility, adaptability, and robustness within the systems engineering community alone. This diversity of definitions is reflective of an immature field and/or one grappling with a complex topic yet to be acceptably solved within a field (Saleh et al. 2009). Reliability is an example of a property that has been studied for a long time and reached a fair convergence in its meaning (at least at the system level); however, the same semantic maturity has not occurred across the broad space of system properties in general.

Even if a universally accepted definition of an engineering system property does not exist, the approximate meaning of the term likely does. Therefore, the existing ambiguity and conflicts in defining properties necessitates providing an explicit definition for any property used for a specific engineering system. This necessitates that each engineering system should maintain its own internally consistent lexicon of system property definitions. Further, in design of engineering systems, it is insufficient to simply specify the requirement “the system shall be resilient.” More specificity is needed, for example, Wied et al. (2020) provide a conceptualization that details categories for resilience “of what,” “to what,” and “how,” the latter including common resilient properties.

An imposed definition for any engineering system property must address the purpose of that property, a means for confirming its existence and ideally a means for measuring its degree and ultimately its value. The *purpose* entails defining the "why" for the property, such as flexibility needed "in order to enable response to uncertainties." Confirming its *existence* entails describing something that can be verified, such as *scalability* displaying some change in level of behavior or *modularity* describing the nature of a system's form. This part of the definition is essential to enable requirements verification (i.e., can we objectively prove that the property exists?). If possible, describing one or more measures that can be used to assess the degree of existence of the property would allow for more nuanced intervention strategies and trade-off considerations. Simply saying that a hospital system has the ability to scale its operations is less useful than being able to say that a hospital system has the ability to scale its operations in terms of number of patients served per hour and capacity of hospital beds. Lastly, if a statement on value can be included, this would enable explicit decisions to improve overall engineering system perceived success. For example, being able to scale hospital operations in a way that is cost-effective, responsive on a timescale demanded during a crisis, while maintaining quality of care, implies numerous measures that could be used to assess different interventions and design and operations decisions that improve the chances for valuable outcomes.

Various approaches used for developing engineering system property descriptions are highlighted, including declared definitions or representations, classification approaches, or even formal semantic bases, as well as description using quantitative measures.

Declared Text-Based Definition and Visual Representations

Many individuals have published definitions over the past few decades. These are, in the end, based on expert-opinion and may or may not have been informed by more rigorous research of the defining individual. Consensus-based declared text-based definitions have been released by several standards groups, including IEEE and ISO/IEC; a list of 27 of these was compiled by Adams (2015). Text definitions are often translated from one language to another, which can lead to additional ambiguity or change the original intended meaning.

Augmenting declared definitions, there have been some efforts to use visual representations of the equivalent of declared text definitions. There are visual representations of a single property and of two or more properties which convey difference (e.g., Chalupnik et al. 2013). Wied et al. (2020) use a set of twelve graph illustrations to show key distinctions between resilient properties. Taysom and Crilly (2014) discuss various diagrammatic representations of system life cycle properties found in the literature and propose a general framework for the diagrammatic representation of system life cycle properties. Idrissov et al. (2020) provide an overview of computer-supported interactive information visualizations found in the literature. They connect four fundamental systems features (relationships, hierarchies, patterns, and processes), information visualizations, and design tasks, providing a mapping for understanding "why certain information visualisations are beneficial to support certain design tasks" (Idrissov et al. 2020).

Definitions alone are perceived by many as insufficient for characterizing engineering systems properties. Chung et al. (2000) and Adams (2015) state nonfunctional requirements have three complicating aspects beyond what some definitions include: (1) they can be subjective (viewed, interpreted, and evaluated differently by different people), (2) they can be relative (interpretation and importance vary on particular system), and (3) they are interacting (attempts to achieve one system property may hurt or help achieving another). Conceptual models (such as a system dynamics representation) are useful to capture such interactions.

Description Using Classification Approach

Classification of engineering system properties is an approach to organize these according to a selected schema or systematic arrangement. As knowledge concerning system properties continues to grow through research and experience, the opportunity to classify these properties in a useful way increases. Adams (2015) states that there is "not a single universal classification schema, framework, or taxonomy." This tends to be widely acknowledged in the broader systems community. Nonetheless, classification approaches are useful, enabling better communication and dialogue on properties.

Various standards and publications have offered classifications of system properties over the years. An example is the 2011 ISO/IEC 25010 (2011) standard, which describes a set of software quality characteristics and sub-characteristics within a quality model. The model has product quality divided into eight high-level properties (called "characteristics"), with several properties considered as lower level "sub-characteristics" within each. The properties are functional suitability, performance efficiency, compatibility, usability, reliability, security, maintainability, and portability. These properties then are each decomposed into sets of additional properties. For example, reliability is composed of maturity, availability, fault tolerance, and recoverability, while maintainability is composed of modularity, reusability, analyzability, modifiability, and testability. While this standard describes various properties within the context of software and computer engineering, interpretations of this standard acknowledge its applicability to other types of systems. This standard has been subject to revision and update (current update is under review) approximately every 5 years (International Standards Organization (ISO) 2011).

More recently, there have been many useful efforts to develop classifications, taxonomies, and frameworks. As knowledge grows, these more recent works often benefit from the prior efforts of various disciplines, especially for the more traditional system properties (e.g., reliability, maintainability, safety, quality). Building on prior the NFR Framework for Software (Chung et al. 2000), Adams (2015) proposes the "NFR Taxonomy for Systems," based on 27 nonfunctional requirements for consideration throughout the systems life cycle that are organized by four concerns: (1) system design concerns; (2) system adaptation concerns; (3) system viability concerns; and (4) system sustainment concerns. This taxonomy also includes a four-level (concern, attribute, metric, measurable characteristic) structural map for measuring them.

Classification approaches vary from author to author, domain, and discipline. These do provide value in organizations properties in various ways that enable designers to discuss and evaluate them. A formal semantic basis is another approach to precision of characterizing properties, as we discuss in the next section.

Formal Description Using Semantic Basis

Given the semantic diversity in describing and even utilizing the system property terms, an alternative approach toward their representation is to avoid assigning definitions altogether. Instead, a "semantic basis" where various aspects of a desired property can be characterized can lend itself to more precisely represent a desired property that may not fit into a particular term label. Ross and Rhodes (2015) proposed such a semantic basis as a construct to promote this alternative consideration of change-type system properties. Using the basis, across multiple categories, the characteristics of the desired property can be unambiguously represented, whether a user wants to label that property with a term such as flexibility, adaptability, or changeability, or not. The benefit of this approach is that it not only avoids semantic confusion (synonymy, the property of multiple terms having similar meaning, and polysemy, the property of [a term] having multiple meanings that are semantically related) but also provides a repeatable, internally consistent representation of system properties that may not yet have a name.

For example, the basis uses the following general form to describe the desired change-related system property:

> In response to "perturbation" in "context", desire "agent" to make a "system change" that results in "outcome change" that is "valuable."

In this syntax, the "X" is one of the basis categories used to describe the desired property. Each of these basis categories can be further subdivided and specified as desired. Figure 1 illustrates both this "6-dimensional" basis, as well as a more detailed "21-dimensional version." The basic idea behind this representation is a state-based concept of change-type system properties, where a system is desired to have some ability to either have a changed state or resist a changed state, in response to an impacting uncertainty (i.e., a "perturbation").

Ility terms, such as flexibility, adaptability, and robustness, are labels assigned to particular choices within the basis (e.g., see Fig. 2 for example ility "labels"). For example, in Ross et al. (2008), specifying the "agent" to be an "external change agent" such as a system maintainer or administrator, along with a "system change" that is "not-same" would result in the label "flexibility" being implied by the statement. Similarly, if the "agent" is specified as an "internal change agent" such as a software agent or system operator and a "not-same" "system change" would

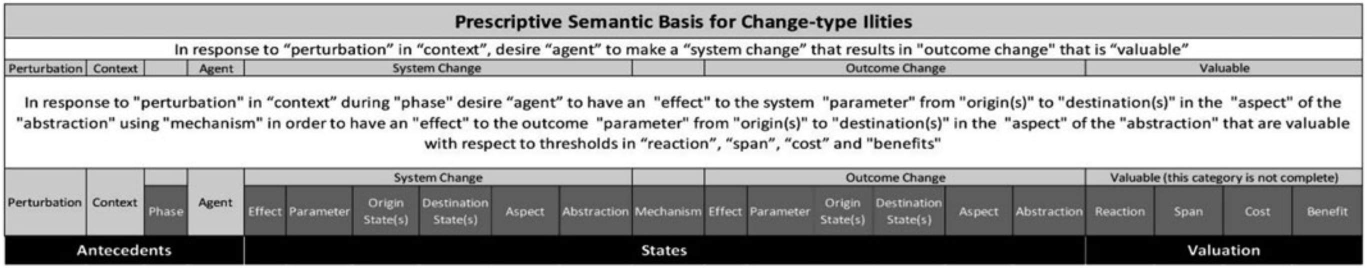

Fig. 1 Example formal prescriptive semantic basis for specifying change-related system properties using a common representation

Perturbation	Agent	System Change	Outcome Change
none	none	decrease	decrease
disturbance	internal	same	same
shift	external	increase	increase
<empty>	either	not-same	not-same
	<empty>	<empty>	<empty>

Example Ility Label	Perturbation	Agent	System Change	Outcome Change
Changeability		either	not-same	not-same
Robustness	shift			same
Survivability	disturbance			same
Adaptability		internal	not-same	not-same
Flexibility		external	not-same	not-same

Fig. 2 Example subset of semantic basis with basis category choices (left) and associated ility label as particular combination of basis choices (right)

result in the label "adaptability." The label "robustness" would apply where the "outcome change" is specified as "same" as a result of "perturbation" (e.g., typically further defined as some context variation, such as variation in weather or driving conditions).

Another benefit toward using such a standardized structure is that it can result in standardized requirements for such system properties. A major challenge in modern system development and governance is effectively communicating, and tracking adherence to, system properties, especially if these are nonfunctional in nature (i.e., if they are *qualities* of performance and cost over time). Standardized requirements can alleviate this challenge by allowing the development of repeatable processes for the creation, verification, and validation of these requirements, for example, writing a requirement that a system be *flexibly scalable in data bandwidth* (from 10 Gbps to 100 Gbps) *in response to increased consumer demand* (number of users from 100 k to 1000 k) at a change cost of less than $1 M in upfront costs and execution time of less than 0.1 s. Using a semantic basis approach enables specification of compound *ilities* statements.

Descriptions Using Quantitative Measures

Quantitative measures for engineering system properties could help verify, validate, measure, evaluate, and even value their presence in an engineering system. But, just as there is wide diversity in definitions of system properties, so too is there wide diversity in quantification of those system properties. Turner et al. (2018) found a "wide number and variety of quantifications" for robustness, a "moderate number of quantifications for interoperability," and a "few quantifications" for agility. This means that there is no prescriptive set of metrics to use for system properties. Instead, defining quantitative measures is best considered alongside the adopted system property definitions used for a particular engineering system.

Connecting back to what comprises a good property description it is one that includes the purpose of the property, a means for confirming its existence, and ideally a means for measuring its degree, and ultimately its value. The latter three items imply the need for a quantitative measure for describing the properties. Ross and Rhodes (2019) link a state-based graph representation of change-related *ilities* to a formal semantic basis that relate to system property terms. In this representation, the antecedents correspond to the existence measure, the states correspond to the degree of measure, and the valuation corresponds to the value measures. For example, if we consider a maritime security system of systems (MarSec SoS) made up of various land, sea, and air assets working together to surveil a littoral region near a port, we can describe various forms of a "flexibility" description. First, we can ask if the MarSec SoS can be changed by an external agent. If the answer is yes, then according to the semantic basis, the MarSec is "flexible." If we further specify that we would like the MarSec to have an external agent change its number of unmanned aircraft (UAV) from 10 to some number between 12 and 15, then we can determine the degree of *flexible scalability* in number of unmanned aircraft. If that change in number of unmanned aircraft must occur within 2 hours and at an operations cost impact of less than \$8 K, then we can determine if it is an *affordably flexible scalable* change. Each of these leverages a specificity enabled by the semantic basis while also utilizing a consistent mathematical representation (here as a graph, with system states as nodes and arcs as change costs between states). In such a representation, a counting metric, such as *outdegree* (*OD*), can be used. A specialized form of this metric is the *filtered outdegree* (*FOD*), which modifies the outdegree by using a series of semantic filters to count only arcs and states that match the property description. Figure 3 illustrates this concept with a graph showing state changes in number of UAV per the above statements. Using the filtered outdegree metric, we can assess a score of 5 for *flexibility*, 4 for *scalable flexible*, and 2 for *affordable scalable flexible*, counting only the arcs and nodes that meet the filter (s) implied by each statement (i.e., external agent paths only, nodes with 12–15 UAVs, and paths that cost less than \$8 K exclusive).

Other quantification descriptions can relate to outcomes achieved as a result of the system property. For example, Rehn et al. (2019) argue that *changeability* is achieved when change effort is low and such effort "can be meaningfully operationalized through two main dimensions for engineering systems: cost and time." Higher changeability means lower cost and quicker change. Likewise, it may be the case that a system property cannot be consolidated into only one quantitative measure. Richards et al. (2009a) proposed two metrics for survivability (time above critical value threshold and time-weighted average utility loss), not as alternative measures for quantifying survivability, but rather as a set needed to cover the multiple dimensions of the property.

Another key consideration when deciding whether and how to quantify system properties is to recognize whether the property is structural/static or operational/dynamic (Giachetti et al. 2003). That is, can the measure be assessed upon inspection, or must the system be observed in action? Typically form-related properties, such as modularity, fall into the former category, while function-related properties, such as resilience, fall into the latter. An additional important consideration is the scale type chosen for the measure. Scale types may be nominal/categorical, ordinal, interval, ratio, and absolute, for example. Each of these types have admissible transformations (i.e., appropriate mathematical treatment) as well

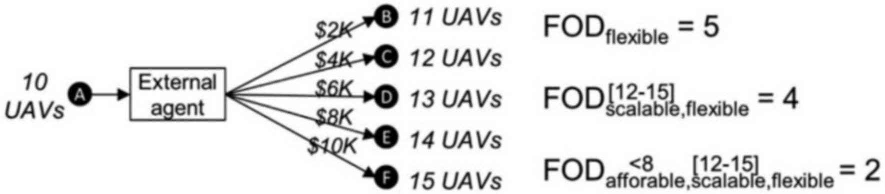

Fig. 3 State change-based representation for change-related system property metrics (FOD – filtered out degree)

as implied ease of use in context (e.g., it may be easier to assign a measure to a low-medium-high ordinal scale than to develop a ratio scale to measure usability of a system).

Regardless of the measure chosen, it is important to be explicit in its definition and consistent in its treatment. Use of common mathematical representations, such as the SoS Analytical Workbench, is one way to ensure representational consistency (DeLaurentis et al. 2017). Regardless of the quantitative approach taken, it is important to recognize that any such treatment necessarily requires abstraction and assumptions that must be documented for transparency and shared understanding across stakeholders of the engineering system.

Considerations for Pursuing Engineering System Properties

The previous section described several approaches to characterizing engineering system properties. This section discusses considerations for the pursuit of desired engineering systems properties, demonstrating the complexities that are involved. Discussed considerations include constraints and influences of the external environment, extent of a property across the engineering system, interrelationship and dependencies, and trade-off between properties.

Constraints and Influences of the External Environment

Desired engineering system properties are not independent of the system's external environment. This environment is comprised of the larger ecosystem and the related exogenous factors. These factors include regulatory, economic, resources, available technology, environmental, market, demographics, and more. The larger ecosystem of the engineering system has many stakeholder groups that are not necessarily directly involved but still may impact the success or failure of the system. Further, this environment is continuously changing, for instance, an independent transportation agency may impose new policy restrictions for a transportation engineering system that limits desired scalability. The influence of public perception and policy positions should not be underestimated. A study by Nickel (2010) found more than half of the factors that determined "success" of a proposed airport express system were outside of the control of the transportation agency.

In considering the design of engineering systems with desired properties, the constraints and influences of the external environment need to be deeply examined. Wied et al. (2018) assert, "resilient properties of the system modify the relationship between performance and conditions under which it operates." Based on a literature-derived classification, these authors propose six classes of resilient properties, including fit conditions to system, fit the system to conditions, fit performance to the system, fit the system to performance, fit conditions to performance, and fit performance to conditions.

Interrelationships and Dependencies Between Properties

Various authors have attempted to describe the relationships between different properties. These efforts are fraught in that the definitions of the properties themselves may vary from author to author. In spite of this, it is still useful to recognize that many system properties are related to one another, for example, they may belong to a semantic field of similar properties (e.g., flexibility, changeability, adaptability), or one may be a means for achieving another (e.g., modularity as a means for achieving reconfigurability). As an example of a means-ends relationship, consider *reconfigurability*. According to Siddiqi and de Weck (2008), reconfigurable systems are those that can change their configurations to potentially satisfy changing system requirements. As they can attain different configurations at different times, thereby altering their functional abilities, the authors state they are "particularly suitable for specific classes of applications in which their ability to undergo changes easily can be exploited to fulfil new demands." Reconfigurability provides a means to achieve *multiability* (system performs multiple distinctly different functions at different times), *evolvability* (system changes easily over time by removing, substituting, and adding new elements and functions), and *survivability* (system remains functional, possibly in a degraded state, despite a few failures). Chalupnik et al. (2013) describe a framework oriented around product reliability, describing robustness, adaptability, versatility, resilience, and flexibility as means for its achievement.

Fricke and Schulz (2005) described the four properties of flexibility, robustness, adaptability, and agility as means for achieving changeability. Boehm et al. (2016) describe an ontology for system qualities where a hierarchy describes means-ends relationships between various system properties seeking to contribute toward mission effectiveness, resource utilization, dependability, or flexibility. de Weck et al. (2011) utilized several approaches to identify correlated system properties as indicated by frequency cited in the technical literature over time, as well as via affinitizing activities by various subject matter experts. One of the findings is that flexibility and resilience are umbrella terms under which other properties can be found and that "agility falls under both umbrellas" (de Weck et al. 2012).

Extent of a System Property Across an Engineering System

A key consideration in the pursuit of desired properties concerns the scope and bounds for emergence of that desired property. Where are designers trying to foster positive emergence – in the engineering system as a whole? At certain levels within the engineering system? In constituent systems in the larger system? Within certain subsystems within a constituent system?

Lee and Collins (2017) state, "for complex engineering systems, such as socio-technical systems, *ilities* as system-level emergent properties are manifest at the subsystem level as well, since subsystems also possess *ilities* emergence characteristics in a similar manner as systems do." They argue that stakeholders "could and should view *ilities* not only as system level properties, but also as subsystem level properties."

Trade-Offs Between Properties

A reasonable question once more than one desirable property has been identified is whether and to what extent an engineering system can, or should, display these multiple properties. Can a system display flexibility and robustness? How does the degree of flexibility change with cost and complexity of the system? The answers to these questions largely depend on the nature of the underlying system itself. In order to address them, assuming these properties are adequately defined, and potentially quantified, the best approach is to use a consistent framework for comparing these properties on a consistent basis. While no universally accepted approach or framework exists, there are many approaches that could be leveraged. The Systems of Systems Architecting for *ilities* (SAI) method is one such approach (Ricci et al. 2014).

In the SAI method, a user follows a sequence of eight steps following identification of an operational need: (1) determine value proposition and constraints, (2) identify potential perturbations (uncertainties), (3) identify initial desired *ilities*, (4) generate initial architecture alternatives, (5) generate ility-driving options, (6) evaluate potential alternatives, (7) analyze architecture alternatives, and (8) trade-off and select "best" architecture with *ilities*. This approach explicitly recognizes that desirable system properties (*ilities*) emerge from the SoS architecture and therefore trade-off of these system properties comes about after considering different architectures with "options" (the means/interventions for achieving *ilities*), rather than analysis of the *ilities* in isolation. In this method, metrics for the *ilities* are defined as a function of how the SoS responds to perturbations, assessed either through modeling and simulation or through subject matter expert judgment guided by the evaluation framework of SAI.

Using a less computationally intensive approach, Corpino and Nichele (2016) propose a methodology, iQFD, using *ilities* in a quality function deployment (QFD) matrix as a supporting tool for inclusion of life cycle properties in early evaluation processes. The need for this is because "*ilities* are usually perceived as 'hidden' desired capabilities, [and] because methods for eliciting them are not mature enough, or fail in the explicit statement of the property attributes when the stakeholders are involved in the decision-making process." The method engages an interview-based quality function deployment process and collaborative sessions of teams of stakeholders, asserting the "strength of the formulation relies on the ability to treat a quantitative measure of the gaps extant between system desired capabilities as perceived by architects, and real end-user needs" (Corpino and Nichele 2016).

Using a different approach, Douglas et al. (2020) propose a framework for evaluating system properties of autonomous behaviors in complex adaptive systems that addresses the issue where "certain stakeholders have interests that go beyond the initial delivery of the system, yet developers seem to focus efforts on designing autonomous behaviours to satisfy immediate mission needs." "Knowledge Acquisition in AutOmated Specification (KAOS) goal modelling methodology coupled with agent-based simulation" is used to help stakeholders identify the appropriate evaluation criteria from desired *ilities*. The initial step identifies key stakeholders and their respective desirable system qualities that benefit them throughout the entire system life cycle. They point out that each stakeholder has a unique interest in the system that may compete throughout the system life cycle, so it is important to identify where conflicts exist for refining the autonomous behaviors, especially as each stakeholder wants to optimize the system at different points during the system life cycle (Douglas et al. 2020).

Regardless of trade-off framework used, it is important to keep in mind that the properties themselves cannot be traded off generally without considering how they manifest in the particular engineering system under consideration. Additionally, care must be taken when describing a system property in general terms, as different "flavors" of a particular system property may trade-off differently. For example, flexibility in a subsystem may trade-off unfavorably with robustness in that subsystem (i.e., more mass and cost to have both), but at the system-level flexibility and robustness may both be achievable with no negative consequences on other measures of interest.

Approaches to Pursuing Engineering System Properties

The previous section discussed several approaches to the characterization of system properties. This section provides insight into approaches for the pursuit of desired properties in two cases. The first is designing for intended properties given anticipated emergent needs. The second case is pursuing system properties to enable the capacity to respond to unanticipated emergent needs. Design principles are discussed as prescriptions for designing interventions for desired system properties.

Designing for Intended Properties

When one or more system properties have been identified, especially when these properties "manifest and determine value after a system is put into initial use" and "concern wider impacts with respect to time and stakeholders," the next question is whether these properties trace to direct needs or ambiguous motivations (de Weck et al. 2012). Anticipating emergent needs reflects an understanding that these particular system properties are motivated by identified challenges that must be addressed at the system's intersection with life cycle, complexity, human behavior, uncertainties, and/or dynamics. In a sense, these "known unknowns" can then be placed into a framework for intentionally creating the system properties. For example, if a system anticipates needing to manage changes in the regulatory environment due to increased emissions standards, one might desire a flexible vehicle platform that allows for modifiability or upgradability of the engine or related hardware or software subsystems. With the ability to anticipate needs, one can leverage previous approaches for achieving the particular *ilities*, for example, by following design patterns, heuristics, or principles that were shown to be effective (Mekdeci 2013).

Beneficial properties, such as scalability in supply in response to increases in demand, can mean the difference between success and failure in the market. One means for "designing for X," where "X" is a desirable property, such as scalability, flexibility (Cardin 2014), or evolvability, is the use of a structured framework for their consideration. Figure 4 illustrates an uncertainty-oriented framework where desirable properties (shown here as *ilities* in response) are those that result in net outcomes that are valuable.

In this perspective, which is an uncertainty-motivated one, responses that appropriately manage impacts are those that are most desired. Uncertainties manifest as threats and hazards (i.e., risks) or opportunities, which then can become looming perturbations, which are imposed change operators on a system state. Unaddressed, these perturbations can push a system into an undesirable state, such as insufficient performance, increased costs, or other failure conditions. To counter this (or to take advantage of the upside of uncertainty manifesting as opportunities), upfront design decisions or later intervention design results in preparations laid inside of the system. These preparations enable later execution of mechanisms to resist or avoid the impacts of the perturbations. For example, decisions to build in power margin in a system allow for excess power to account for increased power consumption demand as a result of a later perturbation. Likewise, stockpiling extra-parts as a preparation allows for later execution of repair mechanisms, with reduced response times, thereby increasing the availability of a system faced with component failures.

Many methods exist to support this type of identification, design, and analysis of responding to uncertainty for engineering systems. These include value-focused architecting methods (Ricci et al. 2014) as well as more directly analytic approaches such as matrix-based methods and those that track change propagations in order to find "flexible design opportunities" where undesirable change propagations are managed (Allaverdi and Browning 2020).

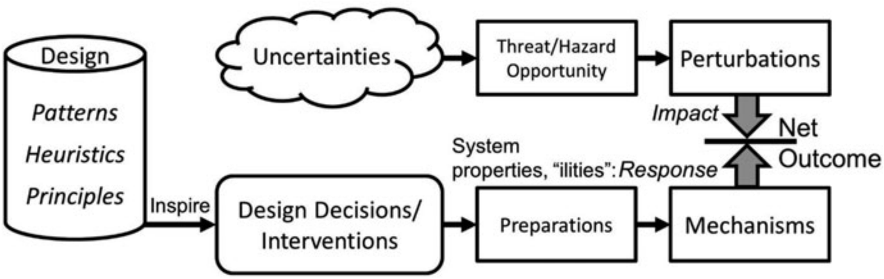

Fig. 4 Design decisions and interventions as a response to uncertainty

Capacity to Respond to Unanticipated Emergent Needs

Emergent needs can be anticipated to some degree by understanding uncertainties that are not expected but could reasonably occur given certain circumstances. One approach that has been taken is rather than planned upgrades and improvements to an engineering system to instead use a pre-planned adaption approach. In the latter, architectural changes are planned at designated points, but what specific changes would be identified, evaluated, and decided later.

It is generally assumed that designing engineering system properties into the system will better enable responding to uncertainties of the future. Justifying upfront expenditure for mitigating uncertainties that may or may not occur is difficult, and there is presently little empirical evidence to demonstrate the return on investment. System lifespan, for example, can be an unanticipated uncertainty. There are many cases of engineering systems that continue to operate beyond the lifespan the designers originally intended; some of these are more successful than others. A recent study by Enos et al. (2020) used grounded theory as a means to identify nonfunctional system attributes, as defined by the engineering system properties, that influence the decision to retire or extend the life of a US defense system. They found that US Department of Defense was more likely to extend life for systems that exhibit extensibility, flexibility, interoperability, robustness, and versatility. Results showed statistically significant difference between attributes of the retired and extended systems. Their work has potential to extend to non-defense systems, and the authors express their belief that "using *ilities* to determine the maturity of a technology and penetration into the market places for products such as software, hardware, and other system level items can help predict what products are targets for market displacement by disruptive technologies" (Enos et al. 2020).

Another perspective that might be taken is one utilized in the complex adaptive systems (CAS) literature, where systems are viewed as only partially designed and partially emergent. For CAS, focus is "on the interplay between a system and its environment and the co-evolution of both the system and the environment" (Choi et al. 2001). In such a view, designing for properties such as flexibility or predictability emerges indirectly as a result of various types of imposed control (either positive or negative) or influence on the system as a result of emerging information over time (i.e., unanticipated). In fact, from the CAS perspective, much of a system may be self-organizing, rather than directly controlled. Therefore "information" and "incentives" are the best ways to guide the behavior of a system in a positive direction, enabling the system to achieve some degree of agility that allows the system to readily "make decisions to redeploy resources to address opportunities and problems" as they arise (Rouse 2008).

Design principles provide the means to inform engineering system interventions that can foster the desired positive emergent property, as well as mitigate or avoid its negation (Lee and Collins 2017).

Design Principles as Prescription for Interventions

Developing responses and interventions do not need to be done as if tabula rasa each time. Prior experience and theoretical foundations for engineering systems can inform reusable advice to inspire these "solutions" for enabling system properties. The history of using design principles, often aimed toward particular system properties, is long. Heuristics and patterns are related concepts.

In the 1970s Atshuller defined 40 inventive principles based on extensive analysis of patents and invention disclosures, becoming part of the TRIZ, Theory of Inventive Problem Solving (Altshuller 2005). Christopher Alexander's influential works on patterns and pattern language, using patterns for defining a problem and providing solutions that fit in the specific context, continue to have broad impact (Alexander et al. 1977). As we discuss in this chapter, design principles refer to an abstraction, or abstract rule, which produces concrete solutions to design problems for a given context. Dove (1999) discusses design principles as emerging from observations of both natural and man-made systems. Wasson (2006) defines a principle as "a guiding thought based on empirical deduction of observed behaviour or practices that proves to be true under most conditions over time."

Design principles provide prescription for creating strategies and structures that can be leveraged for the pursuit of intended engineering system properties. Fricke and Schulz (2005) wrote an influential paper describing design principles that enable design for *changeability* that would enable systems to change throughout their life cycle in response to changes in markets, competition, technology, regulatory, and societal systems. The principles were grouped into basic and extending principles and mapped to what they considered as the four key aspects of changeability: flexibility, agility, robustness, and adaptability. The basic principles mapped to all four aspects; these are ideality/simplicity, interdependence, and modularity/encapsulation. The extending principles map to two or three aspects. These are integrability, autonomy, scalability, non-hierarchical integration, decentralization, and redundancy. Fricke and Schulz consider some properties (e.g., modularity, scalability, etc.) as means for achieving changeability ends. These authors describe both basic and extending design principles and state that in applying principles, "it is important to understand that the principles do have interrelations, which may be useful but also harmful."

Richards et al. (2009b) derived 17 design principles for survivability based on empirical studies, referring to these principles as "concept-neutral strategies of architectural choice." Beesemyer et al. (2011) use a dual descriptive and normative approach in the derivation of design principles and measures for evolvability. Jackson (2016) transformed his initial set of observed resilience heuristics into design principles and subprinciples. He uses the term "design principle" to refer to a broad range of abstract rules that, when followed, produce concrete solutions that improve the system, ranging in rigor from those that are mathematically provable to those that are just guidelines. Over the years, design principles have been applied to many types of engineering systems, especially aerospace, defense, transportation, and infrastructure. Patou and Maier (2017) discuss application of selected engineering design principles to support development of products and services, enabling the bottom-up transformation of healthcare systems. They state this "appears to be particularly important against the background of emerging healthcare model such as decentralisation, personalisation, connectivity, pervasiveness, and stratification."

Evolvability Design Principles

Evolvability design principles guide interventions that will enable the engineering system to evolve over time. Evolvability, according to de Weck et al. (2011), is about "fundamental change to what might be called the DNA of the system – that is the very purpose." They describe evolvability as something that evolves over the long term, involving deliberate initiative to enact – what this handbook refers to as design interventions.

Ricci et al. (2014) propose twelve *evolvability* design principles as shown in Table 2. The first four principles (leverage ancestry, disruptive architectural overhaul, mimicry, exaptation) are considered *strategic design principles* applied to guide direction of analyses and decisions. The other eight principles are considered *structural design principles* applied in the architecting of engineering systems.

Resilience Design Principles

Resilience is a higher-order desired property of engineering systems that is the subject of numerous publications and research efforts in recent years. Wied et al. (2020) performed a literature analysis for the purposes of conceptualizing resilience in engineering systems using three "angles": resilience of what, resilience to what, and how. They identify 12 empirically derived categories of common resilient "how" properties of engineering systems, including *absorption*, *prevention*, and others. Their "how" properties can be equated with what others refer to as design principles. Jackson (2016) distinguishes between *primary principles* and *supporting principles* for enhancing resilience. He defines supporting principles as accomplishing the same goals as primary principles but are at a more narrow scope. A primary principle such as absorption is associated with four support principles: *margins, handling, context spanning*, and *limit degradation*. Jackson also found case studies of resilience suggest that domain (e.g., rail, aviation, healthcare) is a determinant whether a principle is primary or secondary.

Cyber resilience is a desired engineering system property of critical importance in modern engineering systems. Bodeau and Graubart (2017) define cyber resiliency as "the ability to anticipate, withstand, recover from, and adapt to adverse conditions, stresses, attacks, or compromises on cyber resources." These authors also classify their enumerated design principles as *structural* or *strategic*, noting that structural design principles support strategic design principles. This interrelationship demonstrates the importance of designing interventions that consider both dimensions. They state their cyber resiliency design principles can be used, in varying ways and to different degrees throughout the life cycle, and in conjunction with related discipline design principles (security, resilience engineering, survivability, and evolvability). They also make the important point that "selection of strategic design

Table 2 Evolvability design principles (Ricci et al. 2014)

Design principle	Description
Leverage ancestry	Employing successful design choices of assets, capabilities, and/or operations from all prior generations of the system
Disruptive architectural overhaul	Re-architecting significant portions of the existing system or program at the same time in order to reduce the negative impact that making many smaller changes would have
Mimicry	Imitating or duplicating successful design choices of assets, capabilities, and/or operations from other systems/domains for a similar purpose
Resourceful exaptation	Repurposing assets or design choices from prior generations or other systems/domain in order to provide capabilities for which they were not originally selected
Decentralization	Distributing assets, capabilities, and/or operations to appropriate multiple locations, rather than having them located in a single location
Targeted Modularity	Isolating parts of the system to reduce interdependencies in order to limit undesirable effects caused by either uncertainties or intentional changes
Integrability	Designing interfaces for compatibility and commonality to enable effective and efficient integration of upgraded/new system components and constituents
Reconfigurability	Creating intentional similarities in form and/or function of various system assets, capabilities, and/or operations to facilitate reuse or reallocation
Redundancy	Intentional duplication of selected assets, capabilities, and/or operations to enable their future redistribution without compromising existing requirements
Scalability	Making design choices that allow scaling of resources and/or assets up or down in order to accommodate uncertainties and emergent needs
Margin	Architecting for intentional excess capacity in specific capabilities and/or operations to meet emergent needs without compromising existing requirements (i.e., meet or exceed future requirements)
Slack	Intentionally under-allocating or over-allocating specific available assets and/or resources in order to reserve excess capacity for accommodating uncertainties (i.e., prevent violation of constraints)

principles is driven by stakeholder priorities and beliefs, as well as the organization's risk management strategy" (Bodeau and Graubart 2017).

Conclusion

This chapter has provided an overview of the properties of engineering systems and discussed their importance. The motivations for and nature of these properties are described, and several important engineering system properties are highlighted. Design principles are discussed as precursors to designing interventions that foster the emergences of desired engineering system properties, enabling the system to better respond to both anticipated and unanticipated emergent needs.

Design principles serve as prescriptions for specific interventions that enable the design and evolution of an engineering system that possesses the desirable system properties over its lifespan. Engineering systems properties cannot be specified simply by a term (e.g., flexibility), as evidenced by the multitude of definitions that are found in the literature. Future work can mature characterization of desired properties through formalism, such as a semantic basis or quantitative model, enabling desirable engineering system properties to be specified in a more precise and unambiguous manner. Accordingly, this will better inform the design, evaluation, and construction of targeted design interventions.

Designing interventions in engineering systems is complex, and further research is needed to understand how multiple design principles are composed to construct design interventions within the context of current and desired future states of the engineering system. Design interventions are the subject of Part III of the handbook.

Cross-References

▶ Data-Driven Preference Modelling in Engineering Systems Design
▶ Design Perspectives, Theories, and Processes for Engineering Systems Design
▶ Designing for Emergent Safety in Engineering Systems
▶ Dynamics and Emergence: Case Examples from Literature
▶ Engineering Systems Design Goals and Stakeholder Needs
▶ Engineering Systems Integration, Testing, and Validation
▶ Ethics and Equity-Centred Perspectives in Engineering Systems Design
▶ History of Engineering Systems Design Research and Practice
▶ Public Policy and Engineering Systems Synergy
▶ Systems Thinking: Practical Insights on Systems-Led Design in Socio-Technical Engineering Systems
▶ Technical and Social Complexity

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Part III

Designing Engineering Systems Interventions

Engineering Systems Design Goals and Stakeholder Needs

12

Alison McKay, Ole Broberg, and Mark A. Robinson

Contents

Abstract

The engineering systems covered by this book are complex socio-technical systems. Their complexity results from two key characteristics: the technical complexity in their physical manifestations and the elaborate processes, usually operated by people, needed to realise, use, and support such systems through life. Although engineering design tends to focus on technical aspects of these physical manifestations, it is the delivery of the associated processes, e.g., realisation, use, and through-life support, which create value (or frustration) for stakeholders. For this reason, understanding the needs of stakeholders who participate in these

A. McKay (✉) · M. A. Robinson
Socio-Technical Centre and School of Mechanical Engineering, University of Leeds, Leeds, UK
e-mail: a.mckay@leeds.ac.uk; m.robinson@lubs.leeds.ac.uk

O. Broberg
Department of Technology, Management and Economics, DTU-Technical University of Denmark, Kongens Lyngby, Denmark
e-mail: obro@dtu.dk

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processes is critical to the success of the overall system. In this chapter, we consider how one might go about understanding stakeholder needs and formulating engineering system design goals. Three overarching approaches to the design of engineering systems (user-driven design, designer-driven design, and systems engineering) are introduced, and examples of their application to practical design work are provided through three design case studies. One case study relates to the design of a surgical device and the second to the design of a knowledge management system, and the third considers how the approaches introduced in this chapter might be applied when designing in response to sustainable development goals.

Keywords

Designer-driven design · Design case studies · Engineering systems · Requirements management · Stakeholder needs · Systems design · User-driven design

Introduction

The complexity of socio-technical systems, such as the engineering systems considered in this book, arises from two sources:

1. The technical complexity in their physical manifestations.
2. The processes, usually operated by people, often in organisational contexts, needed to realise, use, and support these systems through their lifecycles and decommissioning.

Engineering design processes typically begin with a collection of product or system design goals that are translated into, and ideally quantified as, design requirements. These requirements then drive the development and realisation processes that, in turn, govern the final product or system that is delivered to customers and other stakeholders who enact the product's lifecycle processes. In this way, for large, complex, and long-lived engineered products, what begins as a product design project becomes a large-scale socio-technical systems design project.

The focus of this chapter lies in the journey from a future product's lifecycle processes, and so the needs of people and organisations who form the large-scale socio-technical systems that deliver these processes, to design goals. For large, complex products, this journey is challenging to manage and deliver because the products, and so their lifecycle processes and systems, are often parts of solutions to wider, so-called "wicked" problems (Farrell and Hooker 2013). Farrell and Hooker define three characteristics of wicked problems that make finding solutions, and associated design goals, more challenging than for more simple design problems:

1. **Finitude:** no single individual can establish a full understanding of the whole problem.
2. **Complexity:** the problems include a number of highly interconnected issues, making it impossible to relate actions with consequences.
3. **Normativity:** the problems are parts of [socio-technical] systems whose operations are governed by social and cultural norms that influence both the feasibility and adoption of proposed solutions.

Thus, there are also three associated problems in designing solutions to such wicked problems:

1. The problem itself is not well understood.
2. The interconnected nature of the problem, including stakeholders with multiple allegiances, and so needs, goals, and aspirations, means that it is not always possible to predict the wider impact of proposed solutions.
3. The overall behaviour of the solution is governed by human and organisational behaviours as well as characteristics of the solution itself.

In this chapter, we introduce a range of methods that are used to navigate this journey and so understand stakeholder needs in ways that support the formulation of system design goals and accommodate the ambiguities and contradictions that typify design goals for open-ended design problems. We begin with a review of current state-of-the art approaches to understanding design goals and stakeholder needs. There is no clear step-by-step process for doing this, so this section focuses on three kinds of design process that explore stakeholder needs and design goals in different ways. The first two, in line with Vermaas et al. (2014), distinguish between user- and designer-driven methods, and the third covers approaches to the design of wider systems:

1. User-driven design processes, such as participatory design and user-centred design, where methods used aim to elicit needs and requirements directly from users and other stakeholders.
2. Designer-driven processes, such as parts of IDEO's design thinking process, design ethnography, and Vision in Product Design, which are designer rather than user led and where the focus is on the use of theories and methods from the social sciences to understand and predict future human and organisational behaviours and so future stakeholder needs.
3. Systems engineering and three different ways to look at the systems of which both lifecycle processes and stakeholders are critical parts.

We conclude this section with a framework for selecting appropriate approaches. This is followed by three case studies that are used to provide examples of how these approaches can be applied in the design of engineering systems.

State of the Art in Understanding Stakeholder Needs and Formulating Design Goals

Design goals are important because they drive both creative aspects of design processes and the evaluation of design solutions. More widely, using goal-driven, as opposed to solution-driven, design processes is critical to delivering value to stakeholders. For example, the UK's Crossrail project had cost overruns of circa £600 million (anon 2018), and lesson-learnt reports include recommendations for the management of quality in supply chains and for the use of goal-oriented development processes (Elliot 2018). Design is a key mechanism in delivering quality, especially for engineering systems, where quality covers the reliable delivery of required functionalities to users for which a prerequisite is the effective and efficient operation of the socio-technical systems that deliver through-life processes such as operation and maintenance.

Given that engineering systems are typically designed, produced, and supported through life by networks of organisations, the supply network (which might be better termed the "lifecycle network") is a critical starting point for identifying stakeholders and so their needs and goals.

Figure 1 shows a schematic of the kind of organisational network and so socio-technical system, needed to support the lifecycle of a large, complex, engineered product. The detail balloon expands just one aspect of this network, a prime contractor, its Tier 1 suppliers, and the operators and support service providers of the product in the design and development part of the product lifecycle. Even from this small fragment, the complexities of these networks are apparent (McKay et al.

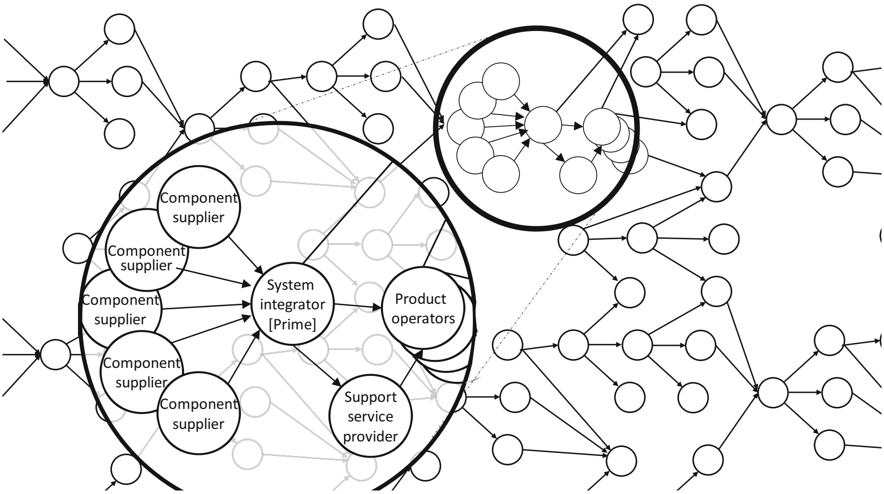


Fig. 1 Lifecycle supply chain schematic (the smaller circles represent organisations, and arrows represent flows of goods, information, and/or money between them)

2013; Kundu et al. 2012). In general, the figure highlights three key factors in the formulation of design goals:

1. The range of organisations and relationships between them in lifecycle support networks creates complexities that are difficult or impossible to untangle.
2. It is infeasible for any one organisation to understand and manage the design goals and needs of the whole network.
3. No single organisation is in a position to control the operation of the entire network.

Fine (1999) discusses similar issues in his book on 3D concurrent engineering, covering the concurrent design of products, processes, and supply networks. For (1) and (2), he suggests identifying an organisation to act as a focal point (e.g., the design organisation) and then considering the needs and goals of organisations two-up and two-down in the network (although he does also provide examples of where such an approach failed to identify supply chain risks). For the identification of design goals, two-up the chain covers the goals of the direct customers of the focal company and their customers (the customers' customers). Two-down the chain implies suppliers and suppliers' suppliers whom, if looking at a lifecycle support network, could include organisations such as maintenance service suppliers and requirements for lifecycle support processes who, in design, take the role of customers. The needs of these organisations can be grouped together as *customer needs*. Two other common groups of requirement influence the needs of each organisation in the network. First, each organisation in the network has its own business requirements, typically to be financially and, increasingly, environmentally and socially sustainable, but also linked to its own strategic goals. Second, for engineered systems, there are usually regulators who provide regulatory requirements.

In what follows in this chapter, we group current practice in understanding stakeholder needs and formulating design goals into three categories. The first two categories cover approaches that focus on the product being designed (which may be a physical product or an associated service). In section "User-Driven Design Approaches", we introduce participatory design and user-centred design-based methods where users and other stakeholders are actively involved in the design process. The second category covers approaches where, for whatever reason, users and other stakeholders are unable to provide a full enough picture of future needs. In these cases, designer-driven approaches, introduced in section "Designer-Driven Design Processes", are used to incorporate social science perspectives and provide insights into future needs and so current design goals. The final category (in section "Systems Approaches") covers systems-based approaches, where the emphasis is on viewing both problem domains and solutions as holistic systems that are connected to parts of other, often wider, systems and situations. Having introduced these approaches, we illustrate their application to three case studies, in section "Case Studies", and we conclude, in section "Conclusion", by considering future avenues for development in both practice and research.

User-Driven Design Approaches

The vast majority of design processes emphasise the importance of understanding user and other stakeholder needs and requirements. Participatory and user-centred designs are two approaches that can be used to achieve this, by bringing users and other stakeholders into the design process. Both approaches can be used in a given design activity but their foci differ: participatory design (section "Participatory Design") builds understanding of stakeholders' needs by including the voices of these people and their representatives in the process, whereas user-centred design (section "User-Centred Design") focuses on the capabilities of target users to inform design goals. However, the two approaches are not necessarily distinct and can be used in complementary ways by human factors practitioners, for instance (Nemeth 2004), where users' affective reactions are also sometimes considered in accordance with Kansai engineering approaches (Bahn et al. 2009).

User-Centred Design

User-centred design (often used synonymously with Inclusive Design or Human-centred design) is about designing *for* users. The concept of user-centred design became widely popular after the publication of a book by Donald Norman in 1986 (Norman 1986), and the Inclusive Design toolkit (Coleman 2017) provides practical methods to ensure that the goals of user-centred design, to make products which have a high usability, are met. The approach is common in the design industry because it leads to increased product usefulness and usability. The International Standard on Human-Centred Design (ISO 9241-210:2019) provides a number of principles that human-centred approaches should follow:

1. The design is based upon an explicit understanding of users, tasks, and environments.
2. Users are involved throughout design and development.
3. The design is driven and refined by user-centred evaluation.
4. The process is iterative.
5. The design addresses the whole user experience.
6. The design team includes multidisciplinary skills and perspectives.

When developing a human-centred system, product or service, four linked design activities take place during the design process: (1) understand and specify the context of use; (2) specify user requirements; (3) produce design solutions to meet these requirements; and (4) evaluate the design against the requirements. In this chapter, we are focusing primarily on the first two activities.

Understanding the context of use includes identifying the relevant user and other stakeholder groups, key characteristics of these groups, their goals and tasks of the overall system, and the environments of use for the proposed system. Methods may include user group profiling and the development of as-is scenarios and personas, as well as participatory design and soft systems approaches. In a system design project, specifying user requirements is a major activity that includes the identification of user needs and specification of functional and other requirements for the system. These can include requirements for organisational changes and revised work styles. In such cases, the development process should involve organisational stakeholders with the aim of optimising both organisational and technical systems. Considering the context of use, the specification of user requirements must (according to ISO 9241-210) include:

1. The intended context of use
2. Requirements derived from user needs and the context of use
3. Requirements arising from relevant ergonomics and user interface knowledge
4. Usability requirements and objectives
5. Requirements derived from organisational requirements that directly affect the user.

The ISO standard further points to potential conflicts between user requirements that should be resolved, ideally by involving the relevant stakeholders.

Participatory Design

Participatory design [Schuler and Namioka 1993] extends user-centred design's philosophy of designing *for* users, to include a wider range of stakeholders, which leads to a key strength of participatory design: its potential to generate design solutions while also involving relevant stakeholders in the design process (Drain et al. 2018). The idea is to bring in real-world users as key stakeholders during the entire design process. It is about user involvement in design projects and design teams. Participatory design is about changing users' roles from being merely informants to being legitimate and acknowledged participants in the design process (Robertson and Simonsen 2018). The participatory design approach has developed widely into many different types of design process. The underlying idea is that the active involvement of stakeholders helps ensure that the design result meets users' needs and is desirable, usable, and affordable. Stakeholders, whether putative, potential, or future, are invited to cooperate with designers, researchers, and developers during the design process. This includes the initial phase where the problem is explored, and problem definition and design goals are established.

Participatory design is also about users and (system) developers learning together about possible and useful technical solutions. It focuses on mutual learning processes. A socio-technical approach and understanding practice are fundamental to participatory design. The term "practice" refers to what people really do in contrast to that envisioned or prescribed in workflow diagrams, for example, and other representations of work and other activities. For example, deep insight into current work practices is emphasised as a starting point for developing and understanding future practice in new or redesigned work-related systems (Robertson and Simonsen 2018).

A number of methods, tools, and techniques have been developed to support participatory design. Typically, the participation takes place in workshops with designers, users, and other stakeholders using techniques such as mock-ups, scenarios, prototypes, and various types of design game. Such tangible artefacts enable prototyping of and design experiments with selected elements of envisioned systems or technologies prior to their development and implementation. Design games were introduced in the participatory design area as a means for designers to involve people in design processes (Brandt et al. 2008; Brandt 2006). Design games help organise collaboration between people with different competencies and interests. Brandt et al. (2008) focus on explorative design games as a way to organise a free space of exploration in collaborative design. They point to board games as a class of participatory design games that have the following features:

1. A diverse group of players are gathered around a collaborative activity, guided by simple and explicit rules and assigned roles, and supported by predefined gaming materials.
2. The gaming materials typically point to either or both existing practices and future possibilities.
3. The games are played within a confined and shared temporal and spatial setting often removed from the players' everyday contexts.
4. The purpose of the game is to establish and explore novel configurations of the gaming materials and the present and future practices to which these materials point.
5. At the end of the game, the players will have produced representations of one or more possible design options (Brandt et al. 2008).

There are a growing number of methods for participatory design of large-scale socio-technical systems. For example, Hughes et al. (2017) have introduced a systems scenario tool and applied it to designing the future of telehealth in the UK, and Jun et al. (2018) demonstrated a participatory design approach to design for safer integrated medicine management. Both include workshops with representatives of many stakeholders and the identification and prioritisation of problems. Systems visualisation in the form of models and diagrams and using tangible materials in workshops are common techniques for enabling the participation of system stakeholders. Finally, Clegg et al. (2017) proposed an approach for predicting malfunctions in complex socio-technical systems, enabling them to be mitigated or prevented proactively, thereby applying organisational psychology as a design science.

Designer-Driven Design Processes

Participatory design methods balance politically grounded ideology with practically driven design priorities to create effective solutions while empowering involved stakeholders to have increased ownership over the final design (Drain et al. 2018). Key benefits of such, user-driven, approaches to design lie in the fact that, as a rule of thumb and although they often have difficulty articulating them, users or their representatives know what they do and don't want and need. So asking them, and creating situations where they can express their needs and wants, is an effective way to elicit them. However, what happens if the users are inaccessible (e.g., in hard-to-reach communities) or if the design is for future needs and wants in the longer term, where today's users are unlikely to know what they'll want or need? Or, where the goal of the design is to deliver wider value? For example, to societal systems as a whole as opposed to individual users alone, though they may, of course, also benefit on multiple levels (Tromp and Hekkert 2019). And, what if we do not know who tomorrow's users are yet, and situations where there are high degrees of uncertainty related to policy decisions and other factors (social and technical) that will affect future users' needs and wants? Designing for these situations requires wider perspectives and the envisioning of future scenarios that inform design goals (McKay et al. 2008). Designing in these contexts demands wider systems perspectives, such as those provided through soft and socio-technical systems-based approaches (see section "Systems Approaches"), which feed information to the designer-driven approaches, based in the social sciences. Before moving on to system approaches, however, here we introduce three designer-driven approaches that are widely used to inform understanding of design goals and stakeholder needs. In section "Design Thinking" we introduce design thinking as a process for addressing wicked problems which emphasises understanding stakeholder needs. Following this, in section "Design Ethnography", we introduce a particular method from the social sciences, design ethnography, which is used in design thinking processes and more widely as a way of building insights into stakeholder needs and design goals. Finally, in section "Vision in Product Design", we introduce Vision in Product Design as a means of envisioning future design goals and stakeholder needs.

Design Thinking

Design thinking is a widely used process that encourages a focus on user and other stakeholder needs. Stanford University's d-school has led the development of educational programs on design thinking (Lewrick et al. 2018; Mabogunje et al. 2016), and perhaps its most well-known proponent is the global design company, IDEO, who provide a brief history of the development of design thinking (IDEO 2020a; Tim Brown 2009). Design thinking processes typically integrate designer- and user-driven approaches along with wider, systems approaches that are introduced in the next section. Key features of design thinking are the cycles of divergent and convergent thinking that it encourages and its aspiration to create solutions that are desirable (i.e., solutions that users want), economically viable (i.e., solutions that users can afford to acquire and use), and technologically feasible (IDEO 2020b). The design thinking process itself includes iterative cycles of three core activities, ideation, inspiration, and implementation (IDEO 2020b). Implementation in each cycle is achieved through the creation of design prototypes. Harrison et al. (2015) explain how the design prototyping process helps uncover stakeholder needs and design goals.

Before moving on, we expand a little of what being technologically feasible means for engineering designers because of its relevance to both design thinking and systems approaches. In essence, it means that solutions can be implemented because the technologies they encapsulate are available and at a stage in their development that makes them accessible to the target market and in the locations where the design will be produced and used. In practice this can be difficult to determine but the notion of technology readiness level (often referred to as "TRL") can be a useful tool for assessing the maturity of a given technology (Wikipedia 2020a). While widely used, there are limitations to the use of TRLs that are highlighted by Olechowski et al. (2020) who review the experiences of practitioners and identify improvement opportunities.

Design Ethnography

Designer-driven design allows broader insights by building on theoretical frameworks from the social sciences, specifically anthropology which studies human cultures and the roles of artefacts in people's lives. Design ethnography is a social science research method that is applied in design to build insights in difficult to access or future design challenges. In an engineering design context, Wood and Mattson (2019) provide a brief history of design ethnography and its application by designers designing for developing communities of which they are not a part. There are also numerous examples in the literature where design ethnography has been used to inform design requirements. For example, Hamzah et al. (2018) report an ethnographic study of paediatric oncology patients that was used to inform the requirements for computer games, and Larsen (2017) reports an ethnographic study of bicycle parking that highlights requirements for cities' cycling and wider mobility infrastructures. In engineering design, a number of authors anticipate the emergence of a new range of tools for use in design ethnography. Dixon et al. (2016) provide a review of the state of the art in computer-aided design ethnography that exploits a range of emerging computational approaches, and example applications are increasingly reported in the literature. For example, Favero and Theuinssen (2018) introduce *EthnoAlly*, a data collection tool that includes a smartphone app and associated archiving and analysis platform.

Vision in Product Design

Hekkert and van Dijk (2016) propose Vision in Product Design (VIP) where designers envision new future scenarios for which they then design and innovate. Their approach encourages analysis of the designs of existing products from three perspectives: the product as a stand-alone artefact, ways in which users and the product interact with each other, and the context within which the product is used. These analyses identify design goals that form the basis of subsequent design processes where the focus lies in designing for future contexts. A series of product design case studies are provided in Hekkert and van Dijk (2016). McKay et al. (2008) outline a similar, context-driven approach that encouraged students to design products for more sustainable futures that they envisioned using research in product-related problem areas for sustainable development such as plastic carrier bags, toys, and mobile phones. A key point for designer-driven approaches to the identification of design goals lies in the designer envisioning future situations and scenarios. Hughes et al.'s systems scenarios tool (2017) can be used to articulate such futures through the description of user scenarios.

Systems Approaches

Current practice in understanding stakeholder needs and so design goals in large complex, engineered systems tend to combine user- and designer-driven approaches to design specific system components, with systems-based methods to provide insights into wider, system-level needs and so goals. For example, results of participatory design processes are often documented in the form of completed game boards, storyboards depicting future scenarios (which consider the design in the system that will form its context of use), and flowcharts defining new processes within these scenarios. If you have used these methods to describe problems you are tackling or potential solutions, then you will probably have noticed that much of the richness you found was not captured. This is because storyboards capture snapshots of a story or experience, and flowcharts really only capture process steps and flows between them. They are fine if this is what you want, but when you are designing solutions that are to form parts of wider systems, you often need more than what you can capture in a flowchart or storyboard.

A system is a collection of interconnected parts that serve some purpose. What this purpose is usually varies depending on the perspective you take. For instance, the purpose of an oilrig from the perspective of its owner may be extract oil, whereas for a consumer of oil-based products, it may be to provide fuel. Both, and numerous others, are valid perspectives that cover the needs of multiple stakeholders. Systems thinking is a useful way to consider stakeholder needs and so design goals, because it provides insights into structures and relationships between elements of the system being designed, wider systems of which it is a part and other systems to which it is connected. For example, systems thinking can allow you to improve understanding of the organisational structures that influence how people behave, appreciate wider implications of proposed changes, and see bigger pictures that may impact the success of the design.

In this section we introduce three systems-based approaches to understanding stakeholder needs and so design goals. Each provides a different kind of view on the system under consideration. In systems engineering (sometimes referred to as "hard systems") approaches (section "[Hard] Systems Engineering"), where the focus lies on physical engineering system interventions, needs and goals are derived from a Concept of Operations (ConOps) (Fairley and Thayer 1997, (Wikipedia 2020b)) and articulated through a target capability statement and design requirements. However, systems engineering approaches provide limited insights to the social dimensions, people, and organisations, of the system. Soft systems thinking (section "Soft Systems Approaches") was established to enable debate and so development of insights into social aspects. Finally, we introduce principles and tools for socio-technical systems design (in section "Socio-Technical Systems Thinking") which provides methods for considering both social and technical aspects of a given system.

[Hard] Systems Engineering

Systems engineering approaches, used in the development of technical components of socio-technical engineering systems, emphasise so-called "hard systems" perspectives in the context of wider user and stakeholder needs. Hard systems perspectives focus on the technical artefacts that are integrated to form larger complex products and socio-technical systems. Blanchard and Fabrycky (2011) is the definitive systems engineering textbook. As such it includes a systems design process, applications of systems modelling, and analysis methods to support the verification and validation of design concepts from both functional and operational perspectives. Blanchard and Fabrycky's systems engineering vee model is widely used in industry, and numerous versions of the model have evolved since it was originally proposed. The UK's Royal Academy of Engineering provides six principles of systems engineering which include using the systems engineering vee model. The RAEng version of the vee model (Elliot and Deasley 2007) is provided in Fig. 2. Key features of all vee models are the flow of design requirements down the left-hand side of the vee; the flow of realised solutions up the right-hand side of the vee; and the zigzagging between the two sides of the vee where parts of systems, components, and subsystems are tested against requirements at each level of decomposition of the system. McKay et al. (2020) provide a version of the vee model that allows its application to the design of systems without the need for a system realisation process. In this model, which is an elaboration of the left-hand side of the traditional vee model, design requirements flow down the left-hand side of the vee, design solutions flow up the right-hand side, and the zigzagging process evaluates proposed designs against design requirements. However, when using

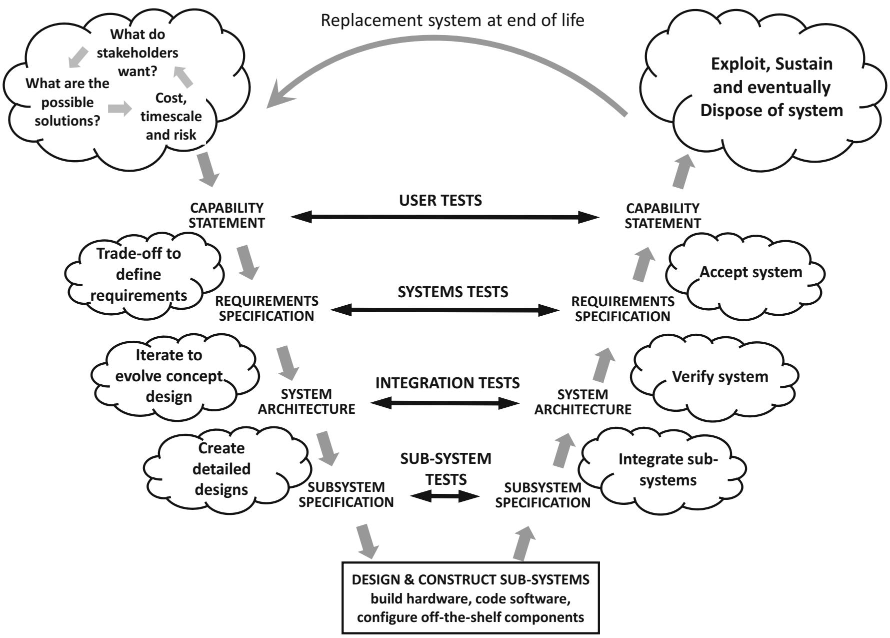


Fig. 2 The RAEng systems engineering vee model. (Adapted from Elliot and Deasley 2007)

these vee models, there is an assumption that the initial design goal, the capability statement in the RAEng model, is an accurate reflection of the stakeholders' needs.

Stakeholders' needs are touched upon in the top, left-hand corner in Fig. 2 with the questions: *What do stakeholders want? What are possible solutions?* and [What is acceptable in terms of] *cost, timescale, and risk?* However, answering these questions is not straightforward. The discipline of requirements engineering emerged in the 1990s as an important part of systems engineering. Hull et al. (2011) provide a process for requirements engineering that is applied at all levels of the systems engineering vee: in both problem and solution domains, i.e., at the top and lower levels of the vee, respectively. The focus of this chapter lies in requirements engineering in the problem domain where the requirements engineering process itself includes four key steps:

1. The elicitation of requirements from within the problem domain
2. Analysis and, where necessary, negotiation of requirements with stakeholders
3. Documentation and specification of requirements
4. Validation of requirements to produce an agreed set of system requirements

A key aspect of systems engineering is the traceability that supports the effective management of change (Hull et al. 2011). Hull et al. (2011) show how traceability and change can be managed within a collection of system requirements, and Agouridas et al. (2006b, 2008) provide a mechanism for relating system requirements to stakeholder needs. In this way, if stakeholder needs change, implications for system requirements can be derived, and the use of a systematic process for deriving stakeholder requirements can help identify previously unseen needs (Agouridas et al. 2006a).

Soft Systems Approaches

While [hard] systems engineering includes methods for considering the wider contexts within which an engineered or technical system will be operated and supported through life, the focus of these methods is on the engineered system rather than the wider system of use and its goals. As requirements engineering processes delve deeper into the needs of stakeholders, the importance of understanding wider, often social and organisational, factors and contexts that influence how they use, work with, and benefit from engineered systems grows. In contrast to hard systems approaches, soft systems methods (Checkland 2000) consider social systems that include multiple people, often belonging to multiple organisations and where both the people involved and their organisations have different, possibly conflicting, goals and values. This focus on wider, social perspectives makes soft systems methods well suited to resolving real-world problems where the development of workable solutions requires debate and different parties gaining insights into others' goals and needs.

Checkland and Scholes (1999) provide a cyclic four stage model for learning from the application of soft systems thinking (see Fig. 3). The process focus on a real-world problem situation, which, in a systems design project, could be captured

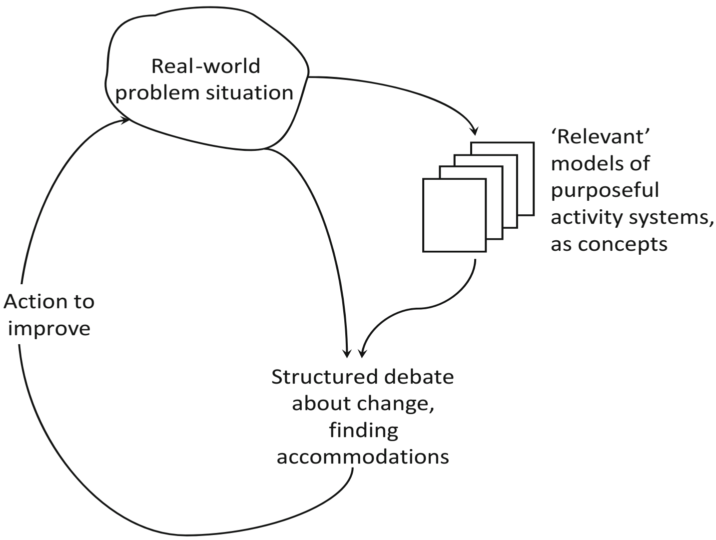


Fig. 3 Checkland and Scholes' four stage learning cycle model. (Adapted from Checkland and Scholes 1999)

in a problem statement or project brief. Based on this, multiple "relevant" models, in the form of rich pictures and conceptual models, are defined and used, in conjunction with wider knowledge of the problem situation, as the basis of a structured debate. Outcomes from this debate are used to identify improvement opportunities (which could be requirements for new engineered systems) and so improve understanding of the real-world problem and so the models and subsequent debates.

As shown in Fig. 3, the soft systems approach begins with the development of one or more rich pictures which are drawings and diagrams that depict the real-world problem situation and the stakeholders associated with it. These inform the development of conceptual models, each of which is a relevant model in Fig. 3. Unlike rich pictures, each conceptual model has a specific structure that includes a root definition and a CATWOE analysis. The root definition defines the purpose of the system in terms of a transformation from the viewpoint of a given stakeholder and is used to inform a CATWOE analysis which identifies the *c*ustomer, *a*ctors, *t*ransformation, *W*eltanschauung (worldview), *o*wnership, and *e*nvironment.

Soft systems approaches are widely used for gaining insights into the operations of human activity systems and in the design and development of IT systems for such contexts (Checkland and Holwell 1997). However, the focus lies on the human activities that drive the system and the delivery of its goals rather than the design of technical aspects of the system itself. In this way, the soft systems approach encourages discussion and provides opportunities for deep exploration of a problem area.

Socio-Technical Systems Thinking

Soft systems approaches are useful in planning and implementing change and for engaging stakeholders in such processes. However, when engineered products and systems are to be parts of solutions, there is a need for more structured approaches. Such approaches need to consider factors that are important to the successful deployment of technological solutions, such as available infrastructures and the capabilities of people who will be interacting with the system. Socio-technical systems design enables this by providing methods to consider systems that include both social and technical components (Clegg 2000; Clegg et al. 2017) and so enables the integration of the hard and soft systems discussed above.

Socio-technical systems approaches emerged from the academic disciplines of organisational and work psychology. The rationale for applying these approaches to systems design is that failure to do so can increase the risk that designed systems will not make their expected contribution to the goals of the organisation in which it will be implemented (Baxter and Sommerville 2011). Socio-technical systems approaches combine two types of system perspective (McKay et al. 2020):

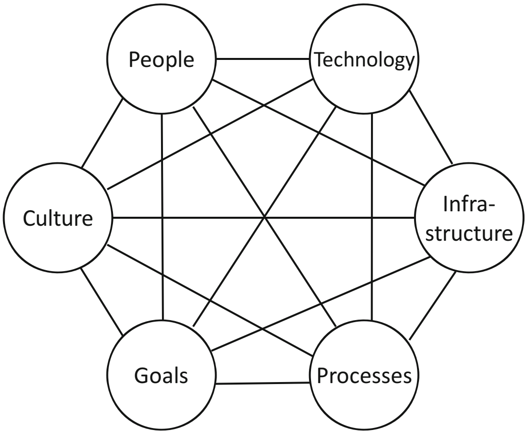
1. *Technical systems* that are produced and continuously adapted to provide a reliable and predictable relationship between user input and the system's output, and
2. *Social systems* that are the result of continuous evolution including emergent changes and behaviours.

As a result, applying the socio-technical systems approaches can result in conflicting value systems. The first set of values is a fundamental commitment to humanistic principles, where the designer is aiming to improve the quality of working life and well-being of employees. The second set is of managerial values, focused on using socio-technical systems approaches to help achieve an organisation's objectives. Problems may arise when these different sets of values come into conflict (Baxter and Sommerville 2011).

Socio-technical systems approaches provide ways of designing systems that include human and organisational behaviours and technology. In this way, they enable the often overlooked but critical social elements of engineering systems to be considered (Robinson and Drury 2020). Some of socio-technical theory draws on the academic discipline of organisational psychology, which considers human behaviour and cognition in work contexts, including organisational processes, culture, and technology (Crowder et al. 2012). More background on the genesis of socio-technical systems approaches and their potential role in design is provided in Clegg et al. (2017). Baxter and Sommerville (2011) also provide a review of socio-technical systems approaches with a focus on the design of computer systems. Socio-technical systems approaches provide insights on how interactions between human and organisational behaviours and technical solutions influence overall system behaviours (Challenger et al. 2010). Clegg et al. (2017) provide a hexagonal framework, shown in Fig. 4 and adapted from earlier work by Clegg (1979), that can be used to represent a given socio-technical system at levels of detail ranging from individual people through to teams and organisations.

Analyses of systems using the hexagon focus on six aspects of socio-technical systems thinking. People, culture, and goals focus on social systems aspects, such as organisational culture, social networks and leadership, and, in this context,

Fig. 4 Socio-technical systems hexagon. (Reproduced from Clegg et al. 2017)



individual and group behaviour and cognition. This includes, for groups, team working, leadership, and communication (Crowder et al. 2012) and, for individuals, competencies, training, and well-being (Robinson et al. 2005). The other three aspects focus on the development and use of technology in social systems, including ways in which technology is integrated with people's work, how this and the design of workplaces and other infrastructures impact performance, and the processes that integrate these. Davis et al. (2014) provide a ten-step description of how to analyse and understand existing socio-technical systems. The range of diverse application areas is illustrated by applications of the approach to case studies, for example, analysing the 1989 Hillsborough football stadium disaster in the UK, implementing environmental sustainability in manufacturing, and preparing for and managing major events, such as the London 2012 Olympics, where a hexagon analysis identified the potential risk factors within the large-scale system that could impact on crowd management and safety.

A key aspect of all forms of systems thinking is the importance of taking a holistic view. For example, in socio-technical systems, there are numerous reports of system failures that can be attributed to a failure to consider social aspects of technological changes and to focus on the development of technology without consideration of wider factors (Clegg and Shepherd 2007). There are several socio-technical methodological approaches that have been developed to elicit information from stakeholders and experts about systemic problems, to identify and mitigate potential systemic failures, and to identify effective systemic processes. We outline two such examples here.

First, Hughes et al. (2017) introduced a systems scenario toolkit to help design or redesign work systems. The toolkit helps explicate the choices made consciously or unconsciously during the design of a work system through consideration of different representative scenarios. The toolkit is a series of workshops and includes six broad stages from involving stakeholders to making choices and agreeing on an action plan to transition from the less effective "as-is" to the more effective "to-be" system. The specific goal of redesigning a work system is therefore realised through the interaction of stakeholders in a workshop. Second, Read et al. (2018) developed a toolkit for information and guidance on analysing complex socio-technical systems, including a requirements identification template. The requirements may assist in planning the system design process, which also includes establishing a design brief and design criteria to help develop a shared understanding of the design goals, both within a project team and between the project team and users and stakeholder representatives.

Overall, thinking about the lifecycle (including use) network of an engineering system is a useful way to identify the stakeholders whose needs it is important to consider. Stakeholder analysis is a tool for understanding the needs of people with an interest in a project (McDonald 2015). Much of the guidance on stakeholder analysis tends to focus on the needs of individual people or groups of people, as opposed to people in organisations whom we also consider here. Once they have been identified, there is a wide range of methods and tools for understanding stakeholder needs, values, and goals.

How to Apply the State of the Art

Thus far, we have introduced a range of methods and approaches that can be used to build an appreciation of stakeholder needs and design goals. While they provide numerous opportunities to gain insights, they also create a problem in that practitioners need to decide which approaches are best suited to the design challenge they are tackling. Accordingly, we provide two categorisations of the approaches that have been introduced. The first, in Table 1, groups the approaches based on the extent to which the design goals are quantified and how structured the approach is. If these approaches are regarded as tools then, like any collection of tools, some are more suitable for different tasks or different stages in a given task than others. For example, design thinking processes and tools are well suited to design processes when empathising with target users, finding out who they are, and understanding their needs is necessary. On the other hand, if the target users are organisations and people in organisational contexts, then more formal requirement management processes from systems engineering are likely to be more suitable. Furthermore, later in

Table 1 Approaches for the development of stakeholder needs and design goals

		Quantification of needs and goals	
		Low	High
Structure in the approach	**Low**	Participatory Design Design Thinking Design Ethnography Vision in Product Design Soft Systems Approaches Socio-Technical Systems Thinking	Although out of scope for this chapter, once design goals and stakeholder needs have been established, early stages of any subsequent engineering design process will include the quantification of needs and goals as part of its requirements definition processes
	High	[Hard] Systems Engineering	User-Centred Design

the process, when a broad understanding of needs has been achieved and design goals are fixed, approaches that involve more quantification of design goals are likely to be more appropriate. For example, the early stages of engineering design processes (Pahl et al. 2006; Pugh 1990; Ulrich and Eppinger 2004) or methods from the disciplines of ergonomics and human factors (Hughes et al. 2017; Read et al. 2018).

A second categorisation scheme is provided by Karsh et al. (2014) who introduce a framework that includes three levels of system decomposition:

1. Macro (relating to industries, nations, and global issues such as the planet and societies)
2. Meso (covering organisations, departments, groups, and teams within an organisation)
3. Micro (including individual people and their immediate work environment).

What constitutes macro, meso, or micro depends on the level of socio-technical system decomposition at which you are working. For example, if you are focused on individual users, then teams may be regarded as meso, whereas if the focus of a design effort is directed towards teams, then the team may be regarded as the micro-level. Referring back to Fig. 1, this can be seen as a meso-level decomposition of the lifecycle system for an engineered product because the elements are organisations within this network. However, this network could also be modelled as a part of a wider, industrial (macro) system, and each part of Fig. 1 could be modelled in more detail as a micro-level system, for example, by detailing the way in which the input to a given organisation is transformed by individual people and teams into its output.

Given the range of methods introduced in this chapter, readers may have the impression that identifying and capturing stakeholder needs, and translating them into design goals, is a straightforward one-off process that sets the stage for a design activity. The reality is somewhat more complex, however, so we conclude this section with two caveats.

1. In practice, design (including understanding stakeholder needs and design goals) is an iterative process where understanding gained later in the process creates a need to revisit earlier stages of the process. For this reason, considering stakeholder needs is an essential theme throughout entire design processes rather than a one-off task.
2. Developing design goals can create ambiguities surrounding what the object of a given design activity is. For example, we are writing this chapter at a time when the need to address climate change is high on many people's agendas. In this situation, the planet may be regarded as a macro-level system in Karsh et al.'s (2014) framework. Although designers can create so-called "green" products and people might use them in large numbers, these actions alone are unlikely to solve the global problem of climate change and often solutions have unintended consequences. For example, the move to biofuels can take land from food production. Individual designers are unlikely to be able to solve such global

issues due to the wicked nature of such problems single-handedly, and the best they are able to do may be to design in the context of wider organisational and societal goals. For this reason, some of the needs and goals uncovered may not become direct design goals; rather, they form contexts within which system design activities are conducted.

Case Studies

We conclude this chapter with three case studies. Two illustrate applications of the methods introduced in section "How to Apply the State of the Art": the first relating to the design of a product for use in a healthcare system and the second to the design of a knowledge management system to connect the design and operations of an oilrig. Both of these case studies build on our experiences from projects where the need to understand design goals and stakeholder needs was critical. With respect to Karsh et al., the first relates to the design of a micro-level engineering system, the design of a medical device for a neurosurgical application. In this example, recognition of individual stakeholders' needs and the resources available to them from the wider system within which the product was to be used were critical factors in the success of the overall design. In particular, there was a need to trade-off accuracy (sub-cm was required as opposed to sub-mm in current solutions) against setup time (10 min was required as opposed to hours or days in current solutions). Second, we complement this example with a meso-level example, based on the development of a knowledge management system to support the design and operation of an oilrig that provides insights into stakeholder needs arising from the lifecycle support for a large, complex product. At this level in the wider system, knowledge management and sharing are important factors in the successful operation of the oilrig and the oilfield of which it is a part (Grant 2013). We finish with a third case study, a macro-level system in Karsh et al.'s framework, that explores the potential applicability of the approaches introduced in this chapter to a current societal challenge, namely, sustainable development. Together, these case studies typify the many sources of design goals that need to be appreciated in the design of complex, socio-technical engineering systems.

Stakeholder Needs in a Medical Device Design Project

Our first case study focuses on understanding stakeholder needs for the design of a medical device for use in neurosurgery based on a user-centred approach delivered through a multidisciplinary student team project involving two product design students, two mechanical engineering students, and a neurosurgeon. The design brief, set by the neurosurgeon, was to design a localisation system for emergency neurosurgery. In such situations, neurosurgeons used localisation technologies to select an entry point when planning surgical procedures. For procedures such as the insertion of ventricular shunts and drainage of blood clots, abscesses, cysts, and tumours, neurosurgeons must operate on the specific regions within the brain that are affected, with an accuracy of less than 1 cm. Two common localisation technologies used at the time of the project to achieve this degree of accuracy were stereotactic frames and image guidance systems. The use of both technologies required the availability of sophisticated equipment (and highly trained staff to operate it) and took a significant amount of resource and time. These constraints made the technologies unsuitable for use in emergency situations where the ability to treat patients quickly is a high priority. In such situations, neurosurgeons typically used their knowledge of the anatomy of the skull and brain to localise the treatment. The goal of this project was to find a more efficient and effective way of localising points in the brain to sub cm accuracy. Efficiency, in this context, was measured in terms of cost, time, and resource utilisation, while effectiveness was measured in terms of responsiveness to clinical needs and reduction of radiation dosage for patients. It was anticipated that this would improve the efficacy and effectiveness of treatments for patients primarily in emergency situations but also with the ability to aid elective procedures. The project resulted in the physical prototype and associated software shown in Fig. 5. These were derived from and evaluated against design requirements, in the form of the demands and wishes (Pahl et al. 2006) shown in Table 2. The prototypes and candidate designs were evaluated against these requirements through analysis, simulation, and user and product testing. The final design, including both physical and software components, was accepted by stakeholders, but a subsequent patent search concluded that the design team did not have the necessary freedom to operate and so the project can be openly discussed.

The design process focused on a real-world problem situation which, in a systems design project, could be captured in a problem statement or project brief, such as the initial design brief in the neurosurgical case. For example, the design team developed soft systems rich pictures and conceptual models that they used to inform discussions with the neurosurgeon who brought wider knowledge that may not have been captured in the models. These models were informed by information gathered from a visit to the neurosurgical unit and discussions with members of the wider team including other doctors and nurses.

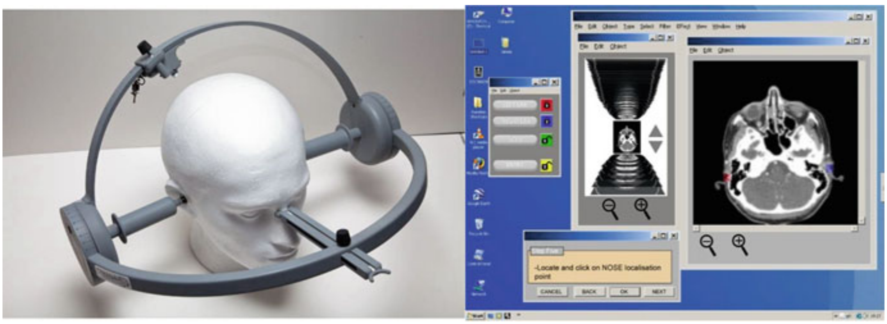


Fig. 5 Illustrations of design outcomes

Table 2 Neuroframe design requirements

Demands	Wishes
The design must: (1) Point to a location with an accuracy of 1 square cm (2) Have a setup time not exceeding 10 min (3) Be inexpensive and intuitive to operate (relative to current methods, i.e., stereotactic) (4) Convert output data from an original CT scan-based software into a physical localisation (5) Be used in conjunction with the Mayfield clamp (6) Be suitable for preoperative use in a marking out/visualisation aid role for making initial marks on the patient's skin	The design should: (1) Be as simple as possible to use (no highly specialised staff required) (2) Be simple to assemble/disassemble (3) Allow the surgeon the required freedom of movement to perform necessary tasks efficiently (4) Be accompanied by a checking rig to allow accuracy confirmation and error checking in use (5) Be applicable to a wide range of emergency situations

The neurosurgical device included wider, system-level needs in its design requirements. For example, in its operation-related requirements, hard systems perspectives identified a need to interface with technical systems within the hospital, such as a Mayfield clamp, a standard piece of equipment in the neurosurgical unit, which led to an operational requirement for the solution to be simple to assemble and integrate with the Mayfield clamp. However, the majority of the design requirements were related to medical priorities (e.g., setup time, use of available data (the CT scan)). The demand for an accuracy of 1 square cm was agreed with stakeholders as a valid interpretation of "sub cm accuracy", and the demand to integrate with a Mayfield clamp was uncovered from discussions with stakeholders. The requirement to be intuitive to use relates to users' previous experiences and expertise, and being suitable for preoperative use was identified as a requirement during user testing when this emerged as an opportunity. From this example, we can see a number of factors that influence relationships between design goals and stakeholder needs and so need to be taken into account in the design of engineering systems. These include the need to iterate design goals through the design process; the importance of engaging with users and other stakeholders, both when defining initial design goals and through the design process; and the importance of building understanding of social and technical aspects of the systems within which a product will be used. All of which are aspects of the design thinking process (Lewrick et al. 2018; Mabogunje et al. 2016).

Lifecycle and Organisational Perspectives from an Oilrig Design Project

Our second case study focuses on the design of a knowledge management system. When complex socio-technical systems are regularly renewed, there is a need for feedback from the operations lifecycle phase into the development and design phase.

In this section, we introduce a case from the offshore oil industry (Conceicao et al. 2019). The company operates a number of offshore drilling rigs and, at the same time, develops and designs new rigs for future operations. For this reason, an oilrig that is functionally excellent on delivery but difficult and costly to maintain and operate is unlikely to be an acceptable solution. Hence, in order to optimise the designs of new rigs, the company wanted to improve the transfer of knowledge and experiences from the operation of rigs into the design processes of new rigs. A group of researchers were invited to improve this knowledge transfer process. Their intervention, using a participatory design approach, was based on involving relevant stakeholders in two workshops with the aim of creating conceptual designs for a new knowledge transfer system.

The case company was organised into two main divisions: operations and engineering design. Thus, the overall socio-technical system included both offshore drilling rig operations and onshore engineering design subsystems. The company had different systems in place for transferring operational information, such as reporting of safety incidents and equipment breakdowns, from the rigs to the onshore headquarters. However there was no dedicated system to capture operational experiences that were important to the design of a new rig.

The workshops were organised by the researchers, each 2 hours in length. The first workshop identified design goals and stakeholder needs, explored the existing knowledge transfer system to understand the current practices, and set systems design requirements. The second workshop developed ideas for design of the knowledge transfer system and setting up systems requirements. The first workshop had five participants from the engineering design division, and the second had eight participants from both offshore rig operations and onshore engineering design. The format of the workshops was based on principles from participatory design and included design games, visualisation techniques, and tangible materials such as game boards and game pieces, as shown in Fig. 6. The researchers, who had agreed workshop goals and rules for "playing" the design games, facilitated the workshops. The participants stood around a table with the game board and game pieces.

The first workshop included two design games aimed at elucidating the current flow of knowledge between the offshore rigs and the engineering design department. Shortcomings and areas that needed improvement were identified. In the second workshop, the main activity was a design game in which the participants simulated a possible new system for knowledge transfer. Based on scenarios, the participants systematically explored how knowledge was captured in the rigs and then transformed, transferred, and applied in the engineering design department. The outcome of the two workshops was a system requirement list for each of the four steps in the knowledge transfer process (Fig. 7): capturing, transforming, transferring, and applying.

This case illustrates how workshops based on design games can facilitate stakeholder participation in identifying stakeholder needs and setting design goals for the design or redesign of complex socio-technical systems. The case especially highlighted two benefits. Firstly, representing the socio-technical system from a bird's-eye view in a game board gave all participants an overview of all processes and structures, even if, in their daily work, they were embedded in a different part of

Fig. 6 Workshop with stakeholders working with design games. (From Conceicao et al. 2019)

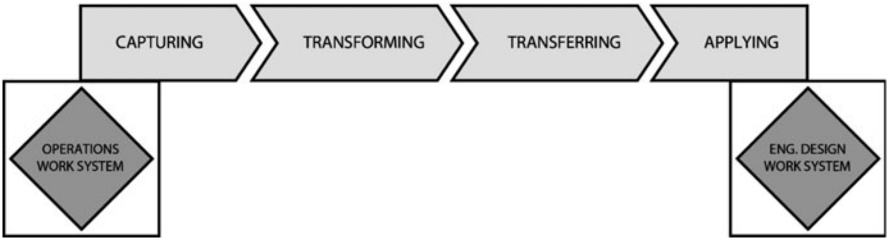


Fig. 7 Four-step model of knowledge transfer from rig operations to engineering design of a new rig. (Conceicao et al. 2019)

the wider system, thereby building shared team mental models (DeChurch and Mesmer-Magnus 2010). Because of stakeholder representation from all parts of the system, it was possible for workshop participants to zoom in and out on specific parts of the system to clarify current practices or explore new ways of working. Secondly, the combination of setting goals and rules for the workshops, having a facilitator who can trigger action, and using open objects as game materials enabled the participants to take a design-oriented approach. They focused on switching between collaboratively exploring current practices and redesigning these practices to improve the overall knowledge transfer system.

The case also illustrates that often it is not possible to identify a single designer or group of designers who are in charge of designing a new system. Rather, there are many potential designers across organisational boundaries, and there are many user groups. Socio-technical systems design is a multi-stakeholder design approach. In this case, the researchers adopted temporary roles as designers to set up a participatory design process, and, through the process, the participants learned about each other's work practices and mind-sets. The simulation activities enabled participants to try out organisational changes, including structure, processes, and tools. Simulating the future knowledge transfer system allowed the stakeholders to learn from practice without incurring real-world risk. Finally, the case indicates that setting design goals is not a one-off occurrence in systems design. During both workshops, both what improving the knowledge transfer system meant and what the design goals should be were discussed continuously. The goals developed and became more specific along the process in the interaction between the stakeholders.

Designing for Sustainable Development

The United Nations (UN) provides 17 goals for sustainable development (2020). Although engineering systems are likely to have a role to play in the achievement of each of these goals, three are particularly pertinent to the development, lifecycle support, and disposal of all engineering systems: promoting sustainable economic growth, ensuring sustainable patterns of consumption and production, and combatting climate change. A real challenge, however, lies in balancing these three goals and the contradictions that they create. For example, manufacturing industries make a significant contribution to the achievement of economic growth but also contribute to climate change and may drive unsustainable patterns of consumption and production. Further, the roots of many of the solutions to issues highlighted through the UN goals are likely to sit in the hands of policy makers and citizens rather than engineers and the systems we produce. Being wicked problems, it is not possible to create single solutions that address all 17 goals. As a result, like today's engineering systems, future engineering systems are unlikely to provide complete solutions. Instead, engineering systems will provide interventions that, in the context of policies and changes in citizens' behaviours, will improve situations and so move us towards achieving the UN goals.

In a recent keynote presentation, Maier and Eppinger (2019) characterised the challenge of designing for sustainable development as a journey. Current approaches such as eco-design and work towards achieving circular economies are early steps in this journey, but there are many challenges to overcome. One of these challenges lies in finding ways to formulate design requirements against which the whole life sustainability of design options can be evaluated as a part of the design process. This, in turn, leads to another challenge in that today's design evaluation tools for large, complex engineered systems apply the laws of physics that govern the behaviour of systems but not how users and other stakeholders use and operate such systems. A prerequisite for improving design evaluation tools in this way lies in gaining deeper insights to stakeholder needs and design goals. In the remainder of this case study, we highlight opportunities for ways in which the approaches introduced in this chapter could contribute.

Systems-based approaches were introduced in section "Systems Approaches". Socio-technical systems thinking encourages the consideration of both technical and social dimensions of a problem as an integrated whole. However, designing large-scale socio-technical systems usually involves the design and deployment of interventions that steer or nudge (Thaler and Sunstein 2009) the system in a more desirable direction rather than creating a radically new system from scratch. This is because there are usually legacy effects, in terms of both social and technological aspects, meaning that we are designing for so-called "brown-field" sites. As such, designers design interventions to existing socio-technical systems rather than design from a blank sheet. Given a design challenge, soft systems approaches can add value by providing opportunities to include a wide range of stakeholders in constructive debate. This allows designers to gain more nuanced appreciations of the people they are designing for and the practicalities of the lives they lead which, in turn, have a significant impact on the viability of proposed solutions.

An important consideration in the use of systems approaches lies in where to draw the boundary of the system under consideration. Draw it too wide and you'll have an intractable problem, draw it too narrow and the system level concerns to be addressed risk being out of scope. Dorst (2015a) proposes frame innovation that can be used as a means of drawing alternative system boundaries. Frame creation is well suited for solving large-scale open, complex, dynamic, and networked problems. A main step in the framework is to reformulate, or reframe, the problem at hand. Creating a frame means developing a novel standpoint from which a problem can be solved. In doing this the system's borders are broadened, and new stakeholders are included. Understanding the goals and needs of the stakeholders in this broader system is a way to open up new solution spaces. Dorst (2015b) provides an example application of frame creation to address a large-scale, complex problem that impacts sustainable development goals. The case involved the construction of a tunnel for the A9 highway around Amsterdam. The tunnel was aimed at improving air quality and reducing sound levels around one of the road's bottlenecks. However, the construction would take about 5 years, and the work would have an environmental impact, including on residential neighbourhoods and office buildings. The design project was characterised by conventional planning and control policies, complex processes, and a tight budget. In a situation with complaints and discontent from affected stakeholders in the area, a suggestion was made to investigate the relationship between the construction works and the surrounding areas by creating a frame. The following frame was identified: "What if you could see the building of the tunnel as a new 'temporary economy'? What new connections could we make then?" (Dorst 2015b, p. 29). In this way stakeholders, including residents, office workers, and commuters, were included in the system design process. By studying the lives and minds of this wider group of stakeholders, new frames emerged for the construction project. The construction project was now seen as a "temporary economy" in which the construction workers were seen as temporary inhabitants who needed to be supported by local services that later on could become permanent. This opened up opportunities for the creation of new initiatives including bespoke food stalls, childcare services, new courses at the local vocational training center, and establishing new local firms to deal with the waste materials from the building works. This case illustrates the value of spending resources on problem framing in the design of large-scale, complex systems. The conventional planning and control approach was complemented by the new frame which regarded the local community as a source of innovation who contributed to a deeper understanding of stakeholder needs and design goals which, in turn, opened opportunities for new design solutions.

With an appropriate capability statement that reflects relevant stakeholder needs and design goals, hard systems approaches can be used to design and develop new improved solutions. However, to include human aspects, designer-driven approaches can be used to complement hard systems approaches. Design thinking processes can facilitate this through their focus on the desirability, viability, and feasibility of proposed solutions. In the context of processes such as design thinking, design ethnography can be used to uncover insights into the needs and wants of hard-to-reach communities and users. It is important to remember that many of the factors that affect the sustainability of design solutions are related to how products are used (and so human and organisational behaviours) and available infrastructures (e.g., to maintain and repair products and to process them at end of life) which affect the feasibility and viability of proposed solutions. Given insights from such processes, however, participatory design and user-centred design can be used to inform the parts of systems with which people (be they users or other stakeholders who support the product through its life) interact.

Conclusion

In this chapter, we have introduced a range of methods used to understand stakeholder needs, and so design goals, in the design of complex engineered products and the socio-technical systems in which they are developed and used. Three case studies were used to illustrate the applicability of these methods to the design of a surgical device, the design of a knowledge management system, and the design of solutions that respond to sustainable development goals. A key aspect of all approaches and the three case studies is the consideration of the wider, socio-technical contexts within which target users and others who have a stake in the product through its life will interact with the product and its effects. Traditionally, the kinds of systems approaches introduced in this chapter have been used largely in the design of high value, complex, long-lived products such as aeroplanes and ships, where operational costs typically exceed (often by an order of magnitude) the costs of developing such products, especially when products or the infrastructures within which they live fail. Increasingly, though, especially given increasing awareness of climate change and societal demands for action, engineering design teams will also need to adopt these approaches for lower value products where stakeholders will include the planet and products will be designed, used, and discarded in the context of closed lifecycle systems such as those promoted by protagonists of circular economies.

This chapter covers methods for eliciting user and stakeholder needs, and so design goals, but systematic processes for using such approaches or translating their results into design requirements remain to be found or defined. What we do know is that the process of developing stakeholder needs and design goals is iterative and continues through the design process as learning about the problem being addressed grows and the product's context of operation evolves. For example, the development cycle for a complex, engineered product can be several years long, in which time information technology advances can have a significant impact on how a product will be used and the technologies that will be embedded within it. A widely used approach for articulating design requirements in the systems engineering community is Concept of Operations (ConOps) which provides, in the language of users, a description of how the product is intended to be operated. While this is useful, a key challenge lies in how design goals and high-level design requirements such as ConOps are broken down into requirements for subsystems. This also affects the translation of socio-technical system-level requirements into product requirements.

In future design practice, we anticipate that designers will increasingly design products in the contexts of wider systems, where they will need to work with less deterministic, more stochastic information such as that related to climate systems and associated with human behaviours. This is likely to become increasingly important in the development of design requirements. As can be seen from the systems engineering vee (Fig. 2), high-level design requirements are not simply decomposed into more detailed requirements; instead, there is a zig-zagging process where solution principles are fixed. Solution principles, in turn, inform both the overall architecture of the product and how requirements are allocated to different aspects. For engineered products that are parts of socio-technical systems, these early, system-level decisions involve the allocation of functions to social and technical aspects of the system (Challenger et al. 2013).

In future research, we see a need for further work on systems design, addressing what can or cannot be designed, what should be left to emerge, and the impacts of local, regional, national, and international policies. There are also emerging opportunities for new methods and interventions through the lives of products, and design practice will need to adjust to this. Technological advances will undoubtedly transform this landscape too, enabling design and other processes such as manufacturing to be more closely integrated through, for example, the increasing use of big data and artificial intelligence in engineering (Tao et al. 2018) and the use of digital twins for simulation (Cai et al. 2017).

Cross-References

- ▶ Choosing Effective Means: Awareness of Bias in the Selection of Methods and Tools
- ▶ Creating Effective Efforts: Managing Stakeholder Value
- ▶ Designing for Human Behaviour in a Systemic World
- ▶ Designing for Technical Behaviour
- ▶ Educating Engineering Systems Designers: A Systems Design Competences and Skills Matrix
- ▶ Formulating Engineering Systems Requirements
- ▶ Human Behaviour, Roles, and Processes
- ▶ Properties of Engineering Systems
- ▶ Technical and Social Complexity

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Architecting Engineering Systems: Designing Critical Interfaces

13

Marija Jankovic and Andreas M. Hein

Contents

Abstract

System architecture is one of the key concepts in designing engineering systems. It relates business strategy and socio-technical system development. System architecture is critical in designing engineering systems as it is a focal point where novel designs are discussed, often in the form of integrating new

M. Jankovic (✉)
Centrale Supélec, Laboratoire Genie Industriel, Université Paris Saclay, Gif-sur-Yvette, France
e-mail: marija.jankovic@centralesupelec.fr

A. M. Hein
Centrale Supélec, Laboratoire Genie Industriel, Université Paris Saclay, Gif-sur-Yvette, France

Space Systems Engineering, Centre for Security, Reliability and Trust (SnT), Université du Luxembourg, Luxembourg, Belgium
e-mail: andreas-makoto.hein@centralesupelec.fr

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technologies into existing system architectures. A key aspect of addressing system architecture is identifying, modeling, and managing critical interfaces. Many studies underline that the success of a development project is based upon managing critical interfaces successfully. Several research domains have been actively contributing to supporting the system architecting phase, developing different system architecture modeling approaches, integrating critical interface modeling, and proposing different system architecture decision support methods and tools. The objective of this chapter is to give an overview of overarching objectives and difficulties in system architecture design and to discuss existing methods and tools both in the literature and in practice. Due to novel challenges in design, such as autonomous vehicles, discussions on new types of architectures have begun, and we provide an overview of existing challenges and potential new domains.

Keywords

Engineering systems · Engineering system design · Interfaces · System architecting · System architecture · System modeling · System of systems

Introduction

In early 1960, the USA decided to pursue the Apollo Program, an engineering system of undeniable historical relevance. Its objective: To put a human on the Moon by the end of the decade. However, the whole program might have failed as soon as in 1961, neither because a particular technology failed nor due to an accident. It was because of a crucial decision related to how the system elements would interact with each other. For landing a human on the Moon, there were essentially three different proposals:

1. Direct. Use a big rocket launcher, which still needed to be developed, to directly launch a spacecraft to the surface of the Moon and directly return from the surface of the Moon to Earth.
2. Earth-Orbit Rendezvous. Use two launchers, smaller than for the Direct proposal, and dock the two pieces of the spacecraft in an orbit around Earth, and then launch the spacecraft to the Moon and perform the same maneuvers as for direct.
3. Lunar Orbit Rendezvous. Use only one launcher, smaller than for Direct, and achieve this by drastically reducing the payload by leaving the return spacecraft in lunar orbit, and land a separate, smaller spacecraft on the Moon; and then go back to lunar orbit, dock the spacecraft to the one in lunar orbit, and fly back to Earth with the spacecraft which remained in lunar orbit.

At that time, NASA pursued option 1 and 2 and rejected 3. NASA rejected 3, as the rendezvous in lunar orbit had not been done before and was considered too risky. However, a NASA engineer, John Houbolt, was advocating for option 3. He showed via detailed calculations and estimates that the rendezvous was not as risky as it seemed. He also showed that options 1 and 2 would require the costly and time-consuming development of a very large rocket launcher, which would make it impossible to land a human on the Moon by the end of the decade. After facing significant internal resistance, Houbolt, in a desperate act, wrote a letter to NASA Deputy Administrator Seamans and was able to convince him that option 3 was the only feasible option for a crewed lunar landing by the end of the decade. This act of desperation ultimately turned the tides, and by 1962, the Lunar Orbit Rendezvous plan was approved.

Why this example at the beginning of a chapter on system architecture? The Lunar Orbit Rendezvous illustrates nicely the importance of system architecture. The architecture in this case includes several components: the rocket launcher, the lunar spacecraft, the rendezvous technology, the ground infrastructure, etc. It also includes relationships between the systems. The rocket transports the spacecraft into space. The spacecraft transports the crew to the Moon and back to Earth. It also shows the importance of system architecture, which is often defined at the early stages of system development. The "right" architecture might lead to a successful system, whereas the "wrong" architecture might lead into inevitable failure.

In this chapter, we will first present definitions for system architecture, a process for system architecting, and modeling principles. Furthermore, we will present some emerging topics in system architecture such as its link to company strategy, system of systems, and product service systems, which are relevant for engineering systems.

System Architecture Definitions

System architecture can be understood as the fundamental structure of a system (ISO/IEC/IEEE 2011). One can identify three major definitions of the system architecture that have been largely used in the literature, which essentially differ in what comprises "structure."

According to the ISO/IEC/IEEE 42010:2011 standard (ISO/IEC/IEEE 2011), a system architecture comprises the "(system) fundamental concepts or properties of a system in its environment embodied in its elements, relationships, and in the principles of its design and evolution." This definition is generic and would apply to various domains such as software architecture and general system architecture.

According to Crawley et al. (2016), system architecture "is the embodiment of *concept*, the allocation of physical/informational *function* to the elements of *form*, and the definition of *relationships* among the elements and with the surrounding *context*." This definition considers the allocation of function to form as essential to system architecture.

According to Emes et al. (2012), the "architecture of a system is its fundamental structure" which may include principles applying to the structure as well as specific structures. This definition is generic and is coherent with the general definition of "architecture" as an object's structure.

Table 1 provides an overview of these three definitions and their main characteristics. It can be seen that each definition considers something different as architecture (concepts and properties, embodiment of concept, structure). Looking at the

Table 1 Comparative table on definitions of system architecture

	ISO/IEC/IEEE (2011)	Crawley et al. (2016)	Emes et al. (2012)
What it is	Fundamental concepts or properties of a system in its environment	Embodiment of *concept*	Fundamental structure
What it consists of in detail	Elements, relationships, and the principles of its design and evolution	The allocation of physical/informational *function* to the elements of *form* and the definition of *relationships* among the elements and with the surrounding *context*	Principles applying to the structure as well as specific structures

elements of architecture, all three definitions stress the importance of system elements and relationships, i.e., its “structure.” Crawley et al. (2016) further develop and add allocation as a particular form of relationship between functions and form, both elements of a system.

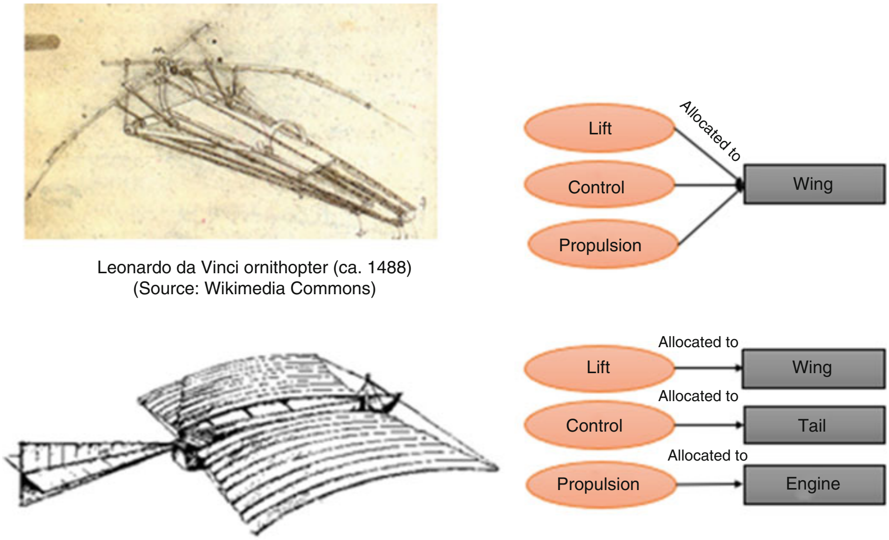
To summarize, although all three definitions are different, they all agree that architecture is some form of the structure of the system, in other words, an abstract property of a system, which is captured in the way elements are related with each other. In the following, we will use the definition by Crawley et al. (2016), as it provides more specific elements for what a system architecture is than the other two definitions.

The importance of the system architecture is manifold. Most arguments for its importance belong to the class of arguments that explain why the early stages of design are important (Fricke and Schulz 2005). The main point is that in the early stages of design, there are still large degrees of freedom for the design of the system. For example, an automobile manufacturer might still be able to choose which type of vehicle to develop (car, motorcycle, tricycle). Once a decision has been made, e.g., development of a car, certain parameters are now fixed and can no longer be changed. A car has a very different set of parameters (e.g., parameters related to the passenger cabin) than a motorcycle (two-wheeled vehicle with no cabin). This process goes on to more and more detailed levels of the design. For example, a car can be a sedan, limousine, and SUV and have a gasoline, diesel, electric, or hybrid powertrain. Choosing one of these alternatives will again fix a set of parameters (e.g., market, size of the car, cargo compartment, etc.). Each subsequent decision will further constrain the parameters, and there are less and less degrees of freedom. From this example, it seems clear that the decisions at the beginning have a more significant impact than the later ones. Later in this chapter, we will look at more complex examples of engineering systems, which go beyond a single monolithic system such as a car and how that affects system architecture decisions.

System architecting as a sequence of decision-making has been proposed by Simmons (2008). However, the question is not only how to better choose between alternatives but also how to innovate or invent, in other words, how do we actually generate new alternatives we then choose from. This is exactly what the Lunar Orbit Rendezvous case illustrates. The question was not only to decide (choose between three alternative architectures) but also to innovate on different levels of the architecture and consider solutions that have never been previously considered.

A historical example for an invention that has its origin in the system architecture is the airplane. An airplane has three basic functions for flying: generate lift, control the airplane, and propel the airplane. The main inventive element for airplanes was how these functions were allocated to the components of an airplane. In 1810, William Cayley published a book called On Aerial Navigation. It revolutionized the field of airplane design. What was his invention? Before Cayley, airplanes were essentially airplanes with flapping wings, called ornithopters. A famous example is Leonardo da Vinci's ornithopter design, shown on the top of Fig. 1. In an ornithopter, the three functions of an airplane are all allocated to one component: the wings. The flapping wings at the same time generate lift, propel the airplane, and are used for control. The objective was to mimic birds. However, it turned out that building an ornithopter was challenging. It was unclear how to improve it, as it was unclear how the behavior of the wings was related to its functions. Hence, the result was rather trial and error, without a clear direction of improvement. For centuries, no substantial breakthrough in airplane design took place.

Here, Cayley comes in. Cayley proposed to allocate each of the functions to different system components. Lift was allocated to the wings, control to flaps, and propulsion to a separate engine. Today, we would call this a modular architecture. Each function was allocated to a different component. By doing so, suddenly, each component could be separately improved by building and testing prototypes. For example, Lilienthal was able to do experiments with gliders (without propulsion and limited control) and measure aerodynamic values, as he could build dedicated experimental setups, measuring a selected number of parameters. Ultimately, the Wright Brothers continued the research program by innovating each of the three



Leonardo da Vinci ornithopter (ca. 1488)
(Source: Wikimedia Commons)

Airplane concept of Cayley (1799)

Fig. 1 Cayley, G. (1810). On aerial navigation. William Nicholson components separately and integrating them gradually to build the first motorized, crewed airplane, capable of sustained flight.

As shown in Fig. 1, one can see that for Cayley's airplane concept, the relationship between function and form was substantially different from its precedent. This invention, together with Cayley's deeper understanding of the physics of flight, would open up a whole new field of research in aeronautics. It demonstrates the power of reasoning around the allocation of function to form.

Another example is the Mars Direct mission architecture, proposed by Robert Zubrin (2011). The Mars Direct mission architecture profoundly changed the way how we can transport humans to Mars and has since then dominated NASA's thinking about crewed Mars missions. The innovation comprised two parts, each involving a different allocation of function to form than previous architectures. First, instead of launching one single spacecraft with a human crew to Mars, two spacecraft would be launched. The first would just transport the cargo to Mars, the second the crew. Splitting cargo and crew means that the cargo can be sent to Mars on a slower spacecraft, needing less propellant, while the crewed spacecraft needs to make the trip to Mars as quickly as possible, in order to limit radiation exposure. The second part of the innovation was to introduce a new technology into the architecture: in situ propellant production. Among other reasons, crewed Mars missions are so costly, as all the propellant for the return trip needs to be carried all the way to the target destination. If that propellant could be produced on-site, the propellant for the return trip no longer needs to be carried to Mars, reducing the propellant mass needed for launching the spacecraft from Earth to Mars. However, producing the necessary amount of propellant takes time, months to even years. Again, allocation played a key role in exploiting the potential of this technology. The cargo spacecraft would transport the in situ propellant production plant to Mars and start producing propellant until the crewed spacecraft would arrive. The resulting architecture is expected to lead to a reduction in cost of up to an order of magnitude. This example shows that typical system architecting activities such as partitioning and allocation of function to form (separation of cargo and crew spacecraft) and infusing the right technology at the right place (in situ propellant production, transported by the cargo spacecraft) can lead to breakthrough results.

System architecture also plays a major role in changing a whole industry. Figure 2 shows trends in complexity increase for integrated circuits, automobiles, and aerospace vehicles. It can be seen that the automotive industry has achieved a decrease in development duration by a factor of 3 between the 1960s and the 2010s, while the complexity of cars increased by five orders of magnitude. This remarkable fact is even more remarkable in light of the number of critical interfaces that has increased (interfaces between different engineering domains needed in system development, interfaces between system components, interfaces between functions). For example, while cars in the 1960s were essentially a set of mechanical components, cars in the 2010s are a combination of mechanical, electronic, and software components. The different engineering domains behind these components need to collaborate. Hence, this increase in critical interfaces adds to the complexity, although this increase in complexity is not even measured by part count and source lines of code in Fig. 2.

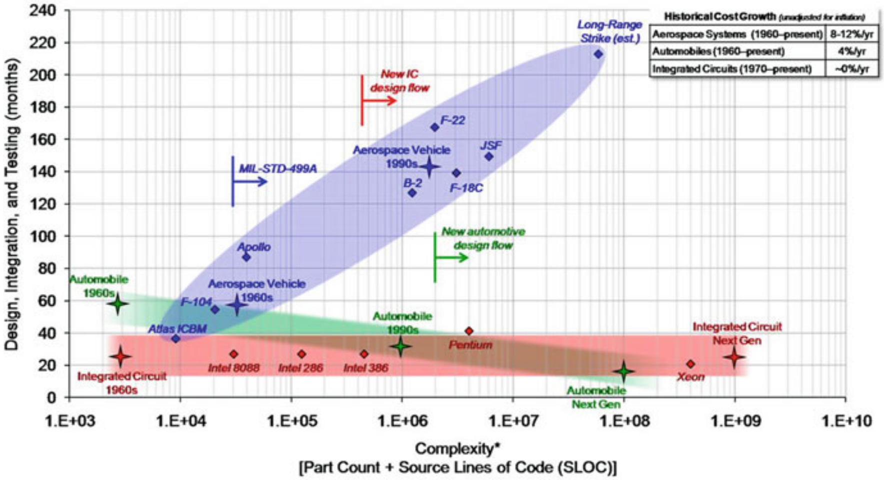


Fig. 2 Trends in complexity and development duration for different industries. (Eremenko, P. (2010, October 7). Adaptive vehicle make [proposer's day briefing to DARPA for the Adaptive Vehicle Make Program]. DARPA Web Site [Online]. www.darpa.mil/WorkArea/DownloadAsset.aspx?id¼42659)

Interfaces between parts as well as lines of code are simply not accounted for. Hence, the "real" complexity increase is much higher.

We have talked a lot about interfaces but what is an interface? We briefly deal with this question in the following. It turns out that it is not easy to respond to this question and the definition of an interface has evolved over time and literature reviews have been addressing this evolution and their definitions (Parslov and Mortensen 2015). Roughly speaking, the majority of the literature considers interfaces as either functional or physical. A functional interface has a function such as transmitting energy out of a component. An example for a physical interface would be a USB port. As mentioned for the example of the automotive industry, interfaces do not only exist between technical components (hardware, software) but also between organizations (teams, departments, companies). Common interfaces between departments in a company are for transmitting data and information. For example, the design department in an automotive company would transmit design drawings to the manufacturing department.

Going back to Fig. 2, one important reason that cars today are developed about twice as fast as during the 1990s is the result of reuse or commonality. Commonality does not only indicate that already existing designs (carryover components) and production lines are reused but also deliberate planning for how designs and production lines can be used across a family of systems, which are under development at the same time. However, designing a family of systems and taking commonality into account is not trivial (Boas 2008). A general trade-off for commonality in a family of systems is between the performance of individual systems and their degree of commonality. The higher the commonality, the more similar the performance of the systems. Often one can observe that initially high commonality values in a family of systems can degrade over time. A reduction in commonality is typically a consequence of using a new design, as a reaction to a lower than expected performance in one of the systems. This phenomenon is called "divergence."

System Architecting

Overall System Architecting Process

Industry has been standardizing the collaborative development of system. This has been done in particular through the definition of system architecture frameworks such as the Department of Defense System Architecture Framework (DoDAF) (Department_of_Defense 2020), NATO Architecture Framework (NATO 2018), TOGAF proposed by the Open Group (The_OPEN_group 2020), MoDAF (Ministry_of_Defense 2020), etc. The aim of these standards is to allow for collaboration while system architecting by providing common concepts. Some frameworks such as TOGAF also provide a system architecting process. The proposed system architecture frameworks have been based upon enterprise frameworks such as Zachman's enterprise framework (Zachman 2006). The main objective of these approaches is to provide a common understanding among different stakeholders in order to be able to collaboratively develop a system architecture. The NATO Architecture Framework (NAF) further specifies that "the purpose of the Architecture Definition process is to generate system architecture alternatives, to select one or more alternative(s) that frame stakeholder concerns and meet system requirements, and to express this in a set of consistent views" (NATO 2018).

Most of these standards propose a:

- Methodology – a process and a definition of how to design system architectures.
- Different viewpoints – these are different conventions of data definition and exchanging data related to the project at different times.
- Meta-model – a definition of a common reference data model that describes the system architecture.
- Glossary – a definition of common terms in order to clarify and enhance collaborations.

The military industry has been developing large systems using these frameworks since the 1940s. They have been also adapted and reworked so as to suit a variety of civil system developments (e.g., TOGAF). Although one could think that there is a wide variety in designing system architectures, the backbone process can be seen as the same (see section "System Definition Phase") that can be refined to fit different purposes of system architecting.

A generic system architecting process may have the following steps:

1. **Identification of stakeholder needs.** Who are the stakeholders and what are their needs that need to be addressed by the system to be developed?
2. **High-level requirement definition** From the stakeholder needs, a set of system-level requirements is derived, which need to be satisfied, defining key functions and performance levels at a high level.
3. **Definition of functional architecture.** What are the functions that need to be executed to fulfill the system-level function(s) and performance? What are the interactions between the functions?
4. **Definition of physical architecture.** What are the system's components, to which the functions are allocated?

It is important that the perspectives advanced in these steps are interrelated. The system requirements are derived from the stakeholder needs, the requirements are satisfied (or not) by the system's functions and components, the functions are allocated to components, etc. A change in one of these perspectives likely leads to a cascade of changes in other perspectives. For example, changing the power of an engine in a car is likely to impact the acceleration of the car, which might lead to a non-satisfaction of the acceleration requirement, which might lead to a customer not satisfied, as the car does not speed up fast enough.

Some system architecting processes introduce an intermediate step between step 3 and 4, the definition of the logical architecture (e.g., OOSEM (Friedenthal et al. 2014)). The logical architecture is commonly used for grouping functions and allocating them to logical components. For example, all functions related to the conversion of power in a spacecraft could be allocated to the logical component "power subsystem," without specifying what technology the power subsystem is based on. The logical architecture introduces another level of abstraction when it is difficult to directly allocate functions to physical components.

A particularly important part of the process of system architecting is the definition of interfaces between functions and components. The interfaces "structure" the interactions between functions and components and influence the system's emergent behavior. These interfaces are so important that even whole industries have developed because of certain interfacing schemes, such as for personal computers (Baldwin et al. 2000). In particular, if the interfaces are defined "correctly," changes do not lead to uncontrollable cascades but are contained within specific areas of the system, which are often called "modules." Modules are of such importance, as they have a low number of well-defined interfaces and "hide" their complexity inside. In fact, industries often develop around such modules, such as industries for motherboards, hard discs, and screens in the computer industry.

System Definition Phase

There are numerous system lifecycle processes and therefore system development processes that are related to the system type, system development context, and different development environments (Haskins et al. 2006). Several very good comparative analyses of system development processes exist and can be found (Haskins et al. 2006). However, whatever the existing process, first stages are entirely dedicated to the understanding of the system stakeholders' needs, system requirements, and, respectively, to the definition of the system perimeter. This exploration (addressing in general step 1 and 2 given in the previous section) is mostly focused until the concept development phase (e.g., exploratory research and concept definition phase (ISO/IEC 15288) or pre-phase A – producing a feasible design by exploring several alternative architectures – to phase C, refinement and completion of build-to designs (Shishko and Aster 1995)). This process is rather generic and stems from identification and definition and stakeholder needs. It extends to mission design and to ConOps (concept of operations) design. These are highly iterative processes and might be differently devised in different contexts. The *NASA Systems Engineering Handbook* (2016) gives an overview of this iterative process and necessary relationships (see Fig. 3).

The interesting point here is that in order to define the system perimeter and thus system architecture that is capturing this perimeter, the *NASA Handbook* identifies the processes stakeholder expectations, requirement definition, logical decomposition (which is in essence system architecture definition), and design solution definition. However, in different contexts, it might be that one starts with stakeholder expectations, to explore requirement definition, to define the ConOps in order to refine the initial system architecture definition (e.g., *INCOSE Systems Engineering Handbook* v3.2 p. 69). Oftentimes, even though these processes can be represented as sequential, they are done iteratively and need to ensure the consistency between them.

Identification of Stakeholder Needs

Identification of stakeholder needs is a critical point for good definition of system architecture. The main objective of this process is "to identify who are the stakeholders and how they intend to use the product" (NASA Handbook). Freeman (1984) underlines that this term was first defined in "those groups without whose support the organization would cease to exist." This definition further evolved to "any group or individual who can affect or is affected by the achievement of the organization's objectives," which is also the definition used in both NASA and INCOSE handbooks. Moreover, the MIT System Architecture Group defines stakeholders as groups that (1) affect directly or indirectly the focal organization's activities, or (2) receive direct or indirect benefits from the focal organization's activities, or (3) possess a significant, legitimate interest in the focal organization's activities (Crawley 2009; Sutherland 2009). The typology that is related to this definition and discussed in this work is the following:

1. "Stake" holders: those who have a direct stake in the project.
2. Beneficiaries: those who derive benefits from the project.
3. Users: the ultimate consumers or users of the project's outputs.
4. Agents: those who act on behalf of other stakeholders in the model.

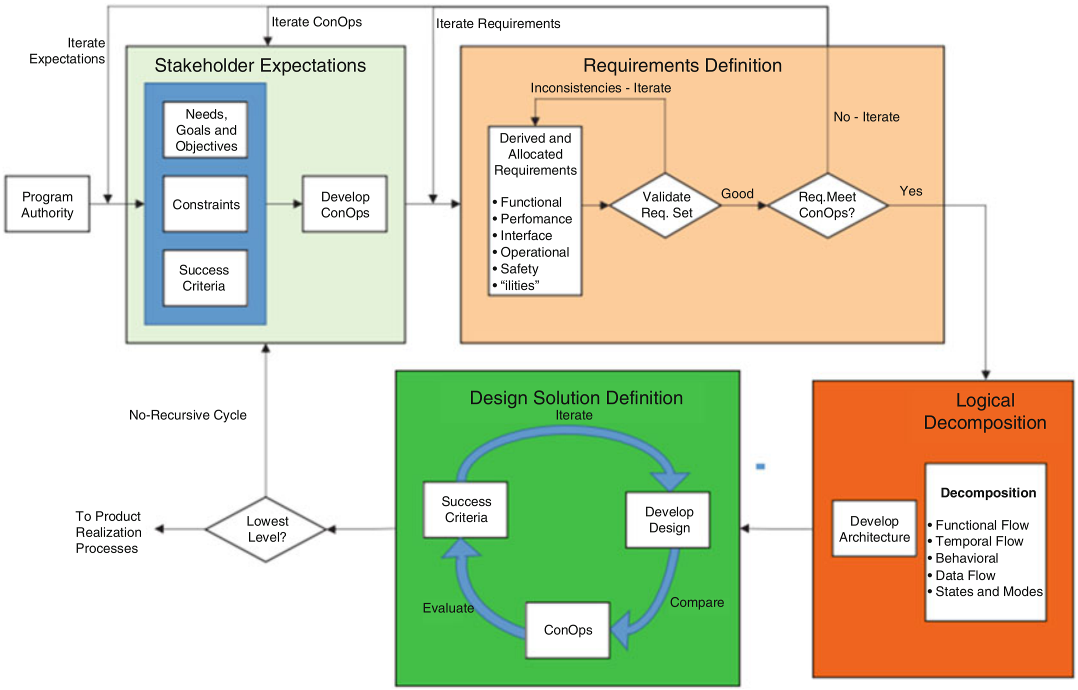


Fig. 3 Interrelationships between early definition processes (NASA Systems Engineering Handbook, SP-2016-6105 Rev2, p. 44)

5. Institutions: official bodies or organizations that directly impact the project.
6. Interests: those with a significant, legitimate interest in the project's outputs, who may not be considered a direct stakeholder in the traditional sense.
7. Project: relatively, the focal organization itself is also a stakeholder in the eyes of other stakeholders.

Several methods and tools are used in order to identify and define stakeholder needs (e.g., marketing questionnaires and surveys, focus groups, prototypes, serious games, virtual reality/simulations). These technics allow either to capture the needs that stakeholders express or to observe what they want and how they use a system in a given situation. Novel approaches to refine stakeholders needs appear such as stakeholder value network modeling (Feng 2013) allowing for modeling and exploring possible value exchanges between stakeholders based on graph theory.

Oftentimes, in order to refine the understanding of stakeholder needs, **concept of operations** is used (ConOps). ConOps represent high-level scenarios of use describing how the system will be used in order to satisfy stakeholder needs (NASA Handbook). The objective of ConOps is to describe and prescribe the intended operation of a system, supporting the understanding of a system context (SE Handbook). In order to be exhaustive, ConOps need to consider all phases of the system lifecycle integrating the knowledge related to off-nominal solutions as well as to develop a as complete as possible set of possible malfunctions and degraded modes. Several modeling techniques are used for ConOPs modeling: scenario modeling, activity modeling (activity diagrams in SySML), process modeling (business process modeling, swim lane modeling), state machine modeling/event modeling, etc. Other than initially discussed objectives, ConOps are also used (SE Handbook) to manage the traceability between operational needs and requirements, as a basis for verification planning, and to generate models to test the validity of external system interfaces, as a basis for calculating system capacity and mission effectiveness.

Stakeholder expectations as well as ConOps are used for the definition of the top-level **requirements** defined in order to understand the technical problem to be solved and establish the "design boundary" or "system boundary." The "design boundary" or "system boundary" is actually the perimeter of the system that needs to be developed. In the system engineering literature, it is addressed as "design boundary" making reference to system design, while in system thinking and modeling, it is addressed as "system boundary" or "system perimeter." This boundary is progressively refined by understanding constraints and limits that the system needs to adhere to, elements and parameters that are endogenous or exogenous (meaning parameters/elements that are within or out of the control and possible change within system design), and external and enabling systems in order to establish possible physical and functional interfaces (mechanical, electrical, thermal, human, etc.).

High-Level Requirement Definition

Many definitions of system requirements exist. The ISO standard defines requirements as a "statement that identifies a product or processes operational, functional, or design characteristic or constraint, which is unambiguous, testable, or measurable and necessary for product or process acceptability" (ISO/IEC/IEEE 2011). For example, Holt et al. define it as "a property of a system that is either needed or wanted by a stakeholder" (Holt et al. 2012). Requirement engineering is a process of encompassing several engineering activities (Berkovich et al. 2014; Jiao and Chen 2006; Song 2017):

- Stakeholders' requirements elicitation
- Stakeholders' requirements analysis
- Requirements specification
- Requirements change management

One of the key activities in these engineering activities is requirement modeling (Albers et al. 2013; Holt et al. 2012; Scherer et al. 2017). According to the recommendation of the IEEE 1233 standards, a requirement model should contain, in addition to the requirement description, the following attributes: unique identifier, priority, criticality, maturity, impact, and possible others (ISO/IEC/IEEE 2011).

The objective of requirements elicitation is to elicit and define system requirements. This process consists of several activities: research, discover, identify, and elaborate client requirements. Zhang identified in the literature four types of requirements elicitation methods: conversation, observation, synthetic, and analytic methods (Zhang 2007). Conversation and observation represent classical requirements elicitation methods and are based on techniques such as interviewing, workshops, and user observations. Synthetic techniques use techniques such as storyboarding, prototyping, and scenarios development. As for the analytic approaches, they are based on more formal and documentation-based methods based often on requirement modeling techniques. Requirement reuse consists of extracting requirements defined and verified in previous projects and using them in a new one. The objective is to reduce development time and cost and increase the productivity and quality of products. Several studies underline that this is particularly useful to help stakeholder rapidly elicit system requirements (Pacheco et al. 2015; Toval et al. 2002). Recycling requirements is slightly different than requirement reuse. It consists in identifying system requirements from previous projects but adapting them to the new one by adjusting requirement parameters and attributes such as maturity, criticality, and flexibility. Alexander and Kiedaisch (2002) defined parameter recycling as keeping the suitable parts in the base of the requirement description, adapting the other parts to the new project's context, and integrating the resulting requirement to the new requirements system (Alexander and Kiedaisch 2002).

System Architecture Modeling Principles

As discussed in previous sections, in order to start addressing system architecture, one needs to define the system perimeter or boundary well. In order to do so, the definition of interfaces that are external to the system is essential. One of the major reasons to build a system is the possibility of emergence. Crawley et al. (2016) emphasize that "the overall functionality is greater than the sum of its parts." However, the other side of the coin of emergency is actually the complexity. The complexity of a system stems from the fact that the system is constituted of many connected, interrelated, and intertwined elements and entities. This leads to the first principle of system architecture modeling: decomposition of different system architecture domains and management of interrelationships, dependencies, and interfaces.

In general, if one looks at different definitions of system architecture, several domains can be identified: functional, structural, and behavioral. This is consistent with the definition of system architecture (for instance Crawley) as well as several underlying theories such us function-behaviour-structure (Gero and Kannengiesser 2004). Each of these domains needs to be decomposed and modeled as well as interrelations between these domains.

Definition of Functional Architecture

The first domain is the functional domain. A system function defines what a system *should do or does*. Modeling system function is a considerable field (Special issue on Function modelling (Vermaas and Eckert 2013)), and several modeling approaches have been identified (Erden et al. 2008). However, two major governing decomposition principles are used when it comes to the decomposition: function decomposition or function flow modeling. Functional decomposition is often identified in companies as functional breakdown structure (FBS) (Dehoff et al. 2009). Several modeling techniques support this decomposition. One of the oldest one is functional analysis system technique (FAST) (Bytheway 2007). The second decomposition principle is actually addressing the order in which the functions may be executed. The technique that is largely used in industry is functional flow block diagram, introduced by Frank Gilbreth (American Society of Mechanical Engineers ASME) in 1921. These two function modeling principles are complementary and not independent. In order to manage engineering system development, functional decomposition is critical for allocating functions to different system levels. However, for each system level, the order of function execution allows for in-depth understanding of how the system functions. The difficulty lies in building coherent and complementary models of functional decomposition and flow and updating them through the engineering system development process.

Definition of Physical Architecture

As for the second domain, **structural domain**, or commonly addressed as *physical architecture* or *form*, the objective of this domain is to identify and describe system components (Browning 2001; Eppinger and Salminen 2001; Yassine et al. 2003; Yassine and Braha 2003) and elements that can achieve certain functions. As in the case of functional domain, one of the two major approaches to address this domain is to decompose. Hence, one of the key tools that govern engineering system development process is the product breakdown structure (PBS). The PBS is not only allowing for hierarchical decomposition of one product but also integrates and reflects the organizational structure of engineering system development (for instance, identification of components that are developed in-house or that are outsourced). Modeling techniques that allow for understanding the system form largely stem from what is called “concept design” or “conceptual design.” Matrix-based approaches have been used since the 1960s (Steward 1962; Steward 1981). Approaches and models using matrices to define form are numerous (Ziv-Av and Reich 2005; Bryant et al. 2005; Jankovic et al. 2012; Maurer 2007). Network-based approaches in a large sense have also been frequently used (Haley et al. 2014; Sarkar et al. 2014; Moullec et al. 2013; Wyatt et al. 2008). The objective of these approaches is to identify and manage interdependencies and in particular system interfaces (Pimmler and Eppinger 1994). For example, Pimmler and Eppinger (1994) define four types of interfaces: spatial, energy, information, and material.

However, considering the functional domain without the structural one often leads to errors and engineering system project failures. In order to understand how the function is fulfilled, allocation of components to functions is necessary to define. “Allocation” or N2 matrices are usually used to define and manage these allocations. Conjoint consideration of these models actually allows for identification and definition of two types of interfaces, which have already been mentioned before: functional ones and physical ones. Functional interfaces represent different types of dependencies between functions. They can stem from functional flows or they can actually be deduced through system structure. For example, if one subsystem or component contributes to the fulfillment of two functions, even though these functions are not connected initially, one can deduce that there is a functional interface to manage. Often this induces also that there are several teams that need to collaborate to make sure that the functions are realized correctly. Physical interfaces are the ones that are identified previously. In particular, the interface definition documents are issued in order to characterize and allow management of these interfaces. However, interface management, as it is also linked to the organization of engineering system management, remains one of the major issues and causes for engineering system project failures.

Behavioural domain is the reason for building systems. Both ConOps and functions are used as proxies early in engineering system design to identify and define expected system behavior. However, actual behavior can be defined, simulated, and calculated only later in the process when more precise models (mechanical, electrical, software) are constructed. However, gathering knowledge and expertise has allowed defining high-level models estimating future system behavior. Models proposed in order to characterize this domain are anchored in value engineering (Miles 2015) or value-driven design (Collopy and Hollingsworth 2011). Cheung et al. (2012) underline that the difficulty lies in analyzing and mapping the relationships between component models to product (system) models to the value model that allows for deciding the most promising system architecture alternatives. The objective is to construct understanding models that go from component models and their design parameters to the overall system value model that allow for the decision. System value models can be also addressed as “-ilities” (overall system costs, system manufacturability, reliability, etc.).

Defining system architecture and system architecture alternatives can be a computationally expensive work. **System architecture** selection is based upon identification and definition of relevant parameters for system architecture selection which is not a trivial task and is often neglected (Moullec et al. 2015). Modeling and representation of possible system architecture performances and their relationship to different design parameter are considered as trade space exploration (Winer et al. 1998; Stump et al. 2002; McManus et al. 2004). The Pareto frontier is used in general in order to identify non-dominated system architectures and in particular to address system architecture trade-offs (Miller et al. 2014; Mattson and Messac 2005; Ross et al. 2004). This approach of multi-objective optimization allows for visualizing and identifying system architecture alternatives having the same trade-offs between two or more system performances.

Implications and Challenges of Systems Architecting for Engineering Systems

Different Company Strategies Articulated around System Architectures

System architecture has been studied and defined as one of the key elements related to enterprise strategy and operation (Fixson 2005). System architecture modeling and organization integrates and is related to different key enterprise strategies allowing for market positioning and share such as make or buy strategy, supply chain organization and management, reuse strategies, distributed development strategies, concurrent development strategies, and development alliances strategies. All these strategies are impacting directly enterprise benefits and success.

One of the determining tactical-level decision processes is related to determining the number and the type of processes that will be used to manufacture a product or a system (Fixson 2005). These processes are commonly addressed as commonality and diversity strategy, implying that if components can be reused across product families or multiple product generations, there is a possibility to manage and reduce cost through scale efforts. This is one of the reasons why system architecting is interesting for industry. In particular, two complimentary strategies (they are not the only ones but here we will focus on them) are used to define commonality and diversity: product family and related platform design and modularity.

A product platform represents a set of parameters or features or components that remain constant from product to product (Simpson et al. 2001). Although it can be features or parameters sharing defining one platform, in the majority of cases in industry product platforms are related to component reuse and sharing. This strategy allows also for product/system personalization while benefiting from reuse strategies. In particular in engineering system design, this strategy is important as it allows also for spreading development costs across different projects and different market segments while maintaining or diminishing the development time. Research studies aiming at understanding, defining, and managing product platforms are many.

Simpson et al. (2001) propose a method for product platform design starting from market segmentation to product platform design. Gonzalez-Zugasti et al. (2000) propose a method to architect product platforms starting from system requirements. De Weck et al. (2003) investigate the method to identity the optimal number of product platforms in order to reduce manufacturing costs.

Related to the definition of product platform strategy is the notion of product modularity. Product modularity arises from the possibility of decomposing products or systems into subsystems. The idea is the possibility for the reuse of these subsystems (Gershenson et al. 2003) and is related to the make or buy strategy. Companies developing engineering systems need to define a comprehensive make or buy strategy (i.e., what is made in-house and what is outsourced), hence creating design chains. In order to be able to outsource developments, there is a need to define subsystems and components in such a way that this is economically interesting and feasible as well as trying to manage interfaces between the module and the system. A considerable body of knowledge exists on the underlying principles for defining product modularity as well as indicators and methods supporting their definition. Gershenson et al. (2003) identify three categories of modularity based on interactions within a product:

1. "Component-swapping modularity, when two or more components can be interchanged in a module to change the functionality of that module
2. Component-sharing modularity, when two or more modules contain one or more of the same basic components as the core upon which they are built
3. Bus modularity, where a module with two or more interfaces can be matched with any number of components selected from a combination of basic components (Huang and Kusiak 1998)"

These strategies aim at managing development times, managing system costs, and increasing product variability while spreading across development efforts.

Although in general, the proposed approaches for system architecting address technical systems and are at the company level, they can be used to support reflections in policy making. One example is the application of stakeholder analysis using the stakeholder value network approach to large-scale infrastructure projects, such as in Feng (2013) and Hein et al. (2017), and space exploration programs (Cameron et al. 2008). Large infrastructure projects and space exploration programs are shaped by public policy, which is the result of finding a consensus between diverse actors (Cameron et al. 2008). Feng (2013) proposes a future work to combine the stakeholder value network approach with system architecture design. Such a combination of stakeholder analysis and system architecting has been proposed in Hein et al. (2018), where societal and public stakeholder concerns are factored into the system architecting process, illustrated by the case of a robotic taxi service. At an even larger scale, system architecting approaches are proposed to address the COVID-19 crisis (De Weck et al. 2020). One of the most well-known research addressing policy making while using system modeling is related to the limits to growth on Earth (Meadows et al. 1972). Meadows et al. (1972) do not address the notion of system architecture explicitly but rather use system modeling, more specifically system dynamics. More recently, however, Hein and Rudelle (2020) have assessed the limits to economic growth on Earth by combining approaches from ecological economics and energy economics, with system architecting approaches such as technology infusion. Their objective is to derive recommendations for long-term decision-making in energy and climate policy making.

We expect that the tendency of using system architecting (or system modeling principles) in policy making is growing even more because of the interconnectivity of systems that give emergence to novel types of systems such as system of systems or product service system of systems (Hein et al. 2018). These systems not only have a technical aspect to address but also integrate societal challenges into system architecting processes.

Integrating Systems: Notion and Challenges Related to System Architecting of System of Systems

System architects are more and more confronted with the integration of individual systems, managed and operated independently, into a higher-level system. Examples are multimodal mobility, where different transportation systems such as trains, busses, and taxis are integrated to provide an integrated mobility service. The train system, bus lines, and taxis are typically operated and managed by different entities. Nevertheless, busses might get informed about a train arriving late and need to wait for passengers. A taxi might be redirected, as a passenger stepped out at the wrong train station. Hence, data is exchanged between the constituent systems. Such collaboratively integrated systems are called "system of systems" (Maier 1996). Although there is no consensus definition of a system of systems, several definitions have in common that each constituent system is independent and has its own purpose (Boardman and Sauser 2006). Some system of systems satisfies the criteria of engineering systems such as the electric grid, public transportation, and the healthcare system.

System of systems has characteristics which make their design challenging, and existing system engineering approaches have limited applicability (Sousa-Poza et al. 2008; Keating et al. 2003). As its constituent systems are managed and operated independently, forming a system of systems is also a collaborative challenge. This may require not only the consideration of the architecture of technical systems but may require the consideration of the architecture of collaborating organizations, also referred to as enterprise architecture (Cole 2009). Another hallmark of system of systems is that their constituent systems have their own purpose and independence (Boardman and Sauser 2006; Maier 1996). For example, a bus can be operated on its own and has its own purpose. This is in contrast to an engine in a car, which does not provide value without being integrated into a car. Furthermore, as data and information need to be exchanged between constituent systems, common data formats, standards, and protocols need to be established. As with all systems, system of systems has emergent behavior, which might only be discovered through experiments of gradual interventions (Meilich 2006). Traditional systems engineering defines system boundaries at the beginning of the architecture design process. System of systems tends to have shifting boundaries, which change over their lifecycle, due to the introduction of systems, technologies, or changing requirements (Keating et al. 2003). For example, new modes of transportation could be introduced into a multimodal transportation system, such as electric scooters.

System of systems is also rarely designed from scratch and is subject to interventions to existing systems. System of systems evolves over time and might be subject to constant change (Maier 1996). They might emerge (train lines and bus lines exist in parallel initially but are then integrated) or evolve gradually by integrating more and more systems. Hence, the architecting process of system of systems rarely follows the typical system architecting process but is rather iterative with incremental modifications, which may take place at different speeds. Although approaches for architecture design of system of systems have emerged, they seem to be rather mature in the area of defense and security (Meilich 2006). For other domains, architecting system of systems seems to be rather on an ad hoc basis, and it seems that there is a lack of systematic approaches (Keating and Katina 2011).

System of systems also evolves on different time horizons. For example, a multimodal transportation system is dynamically reconfigured within minutes to hours (train stops operating; replacement busses are put in place). However, the definition of a new bus line might take years and might start with a low frequency which is then gradually increased. These different time horizons require different architecting approaches. For example, dynamic reconfiguration during operation may be accomplished by semiautomatic system reconfiguration approaches (Qasim et al. 2019, 2021). For longer time horizons, such as for a new bus line, traditional architecting approaches, including stakeholder analysis, may be appropriate (Feng 2013).

These specific system of systems characteristics require architecture models which specifically represent the following critical interfaces:

- Collaborative relationships between actors managing/operating constituent systems.
- Defining data exchange standards, protocols, and interfaces has a disproportionate importance, compared to traditional systems.
- Evolutionary development. System of systems is usually not developed from scratch. They evolve over time. This requires the consideration of different lifecycles of constituent systems and how new systems can be integrated into the system of systems and how the exit of systems might affect the system of systems.
- Different timescales. The behavior and evolution of system of systems have different timescales which might range from microseconds to years. Different behavior models are necessary for adequately simulating and taking into account these different timescales. These different timescales also impact the choice of the system architecting approach, e.g., dynamic reconfiguration of the architecture during the operations phase vs. architecting during the design phase.

Toward Product Service System Architectures

Another type of emerging engineering systems is system with the objective of delivering services. Examples for such systems are the healthcare system, multi-modal transportation systems, and the energy supply system. These examples are similar to those we have given as examples for system of systems, which is not a coincidence. However, for now, we focus on the delivery of services by these systems. Services are gaining more and more in importance, and traditional manufacturing industries such as automotive and aerospace are undergoing a profound transformation. For example, instead of selling airplane jet engines, today, jet engine hours in operation are sold to customers. In the automotive domain, mobility services such as car-sharing are starting to substitute personal cars, particularly in large cities. Hence, the challenge is to understand how to design such systems combining products (e.g., car) with a service (e.g., mobility). These types of systems are referred to as product service systems (PSS) (Tukker and Tischner 2006). To come back to the examples we gave at the beginning of the paragraph, here we want to address specifically emerging engineering systems that are PSS. These PSS are typically at the same time *system of systems* (Hein et al. 2018). In terms of modeling the system architecture of such PSS, existing models for system of systems need to be extended, to represent services in more detail (Hein et al. 2018).

PSS that are engineering systems add an additional service, business, and societal perspective to system architectures (Hein et al. 2018). As a consequence, traditional system architecting with its representations of stakeholder needs, requirements, functional architecture, and physical architecture needs to be extended. For example, the introduction of autonomous vehicles adds a service layer to the architecture, where transporting a passenger from A to B at a given cost and duration is a service in that layer (Hein et al. 2018). Furthermore, while traditional system architecting often deals with development "from scratch," PSS which are engineering systems are rather designed around *interventions* into an existing system, for example, using existing infrastructure elements and services (Hein et al. 2018).

While in traditional system architecting, the system boundary needs to be defined early on, in order to define the system's concept of operations, in engineering systems PSS, we know the service and the desired service quality, but we do not necessarily know the boundary of the system and might decide in run-time or during systems operation which solution we choose (cloud or on-site server). These shifting system boundaries can be modeled by defining alternative solutions that are used under certain conditions or rules. A typical approach for defining alternative solutions, extensively used in software engineering, which is suited for PSS is feature models allowing to define features that represent customer-related characteristics of a product or a service.

While the PSS literature oftentimes represents services as functions, one of the challenges is that emerging services are collaborative, involving multiple actors, and involve multiple systems and infrastructure elements that are dynamically reconfigured (Fakhfakh et al. 2019). Such services rely on a system of systems (a set of independent systems) and combine multiple lower-level services. Hence, in addition to the interfaces which are created between individual systems in system of systems, engineering systems PSS further add interfaces between services as well as between services and systems.

Conclusions

System architecting has been a cornerstone activity in defining systems that are durable and sustainable and with long lifespans. System architecture is critical in designing engineering systems as it is a focal point where novel designs are discussed. A key aspect of addressing system architecture is identifying, modeling, and managing critical interfaces. System interfaces have been identified as a key point in designing, modeling, and managing system architecture. Best practices, methods, approaches, and tools have been developed actively by different communities, both academic and industrial, in order to support this process as it has been clearly identified as key to business development strategy as well as overall company success. A considerable body of knowledge has been developed in order to support system architecting, and this collaboration process involves numerous and different stakeholders.

Nowadays, systems are changing. They are becoming more complex, integrating new technologies such as Internet of things, cloud computing, big data, etc. These novel technologies add novel layers to systems that are to be developed and increase the notion of services. This extension is adding critical interfaces to system architecture, which need to be identified and managed. For example, in system of systems, individual systems are collaboratively integrated, introducing interfaces between actors and systems, as well as between systems. Product service systems (PSS) as another example of system of systems introduce interfaces of collaboration between actors but also introduce interfaces between products and services, as well as between services.

These challenges actually become even more critical as sustainability issues and challenges for sustainable design increase the need to foster and support system architecting in order to propose systems that are more durable, reconfigurable, upgradeable, or flexible. Engineering systems are essential in maintaining the functioning of our society, in a context of diminishing resources. Hence, system architecting seems yet to be discovered and supported to advance collaboration to better our future at a global level.

Cross-References

▶ Choosing Effective Means: Awareness of Bias in the Selection of Methods and Tools
▶ Design Perspectives, Theories, and Processes for Engineering Systems Design
▶ Designing for Technical Behaviour

▶ Engineering Systems in Flux: Designing and Evaluating Interventions in Dynamic Systems
▶ Properties of Engineering Systems
▶ Public Policy and Engineering Systems Synergy
▶ Roles and Skills of Engineering Systems Designers
▶ Technical and Social Complexity
▶ The Evolution of Complex Engineering Systems

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Data-Driven Preference Modelling in Engineering Systems Design

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Wei Chen, Faez Ahmed, Yaxin Cui, Zhenghui Sha, and Noshir Contractor

Contents

W. Chen (✉) · Y. Cui
Integrated Design Automation Laboratory, Northwestern University, Evanston, IL, USA
e-mail: weichen@northwestern.edu; YaxinCui2023@u.northwestern.edu

F. Ahmed
Design Computation and Digital Engineering Laboratory, MIT, Cambridge, MA, USA
e-mail: faez@mit.edu

Z. Sha
System Integration and Design Informatics Laboratory, The University of Texas at Austin, Austin, TX, USA
e-mail: zsha@austin.utexas.edu

N. Contractor
Jane S. & William J. White Professor of Behavioural Sciences, Science of Networks in Communities Laboratory, Northwestern University, Evanston, IL, USA
e-mail: nosh@northwestern.edu

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Abstract

In this chapter, data-driven approaches for multi-stakeholder decision-making in engineering systems design are discussed. Specifically, we underscore the need for modelling customer preferences in engineering systems design for understanding the interactions among multiple stakeholders in a complex design ecosystem. This chapter starts with an introduction to multi-stakeholder decision-making in complex engineering systems and existing research on multi-stakeholder decision-making. Then it uses the market as an example of an engineering system to demonstrate how an enterprise-driven decision-based design (DBD) approach can support rigorous engineering design decisions. Next, an overview of existing data-driven approaches like value-based models, agent-based models, and network-based models for customer preference modelling is given from which the limitations of commonly used utility-based customer preference modelling techniques are identified. This chapter shows how such limitations can be overcome by modelling heterogeneous customer preferences and choice behaviours based on the science of complex networks and theories from the social sciences. Two case studies on vehicle systems design highlight the steps of network-based customer preference modelling and demonstrate its advantages in visualising and modelling the complex interdependencies among different entities in a design ecosystem for data-driven design interventions. These examples provide insights into various factors considered by customers in buying cars. At the end of this chapter, challenges associated with the use of data-driven approaches for customer preference modelling are examined together with an outlook for future research opportunities in this topic area.

Keywords

Customer preference modelling · Data-driven · Engineering systems · Enterprise-driven design · Multi-stakeholder preference · Network modelling · Vehicle design

Introduction

Complex engineering systems contain multiple types of stakeholders and many individual entities, which exhibit complex interactions and interconnections. In such systems, the system-level objectives like the technical, social, economic, and environmental performance of the system are often affected by the individual behaviour and decisions of heterogeneous stakeholders. A typical example of a

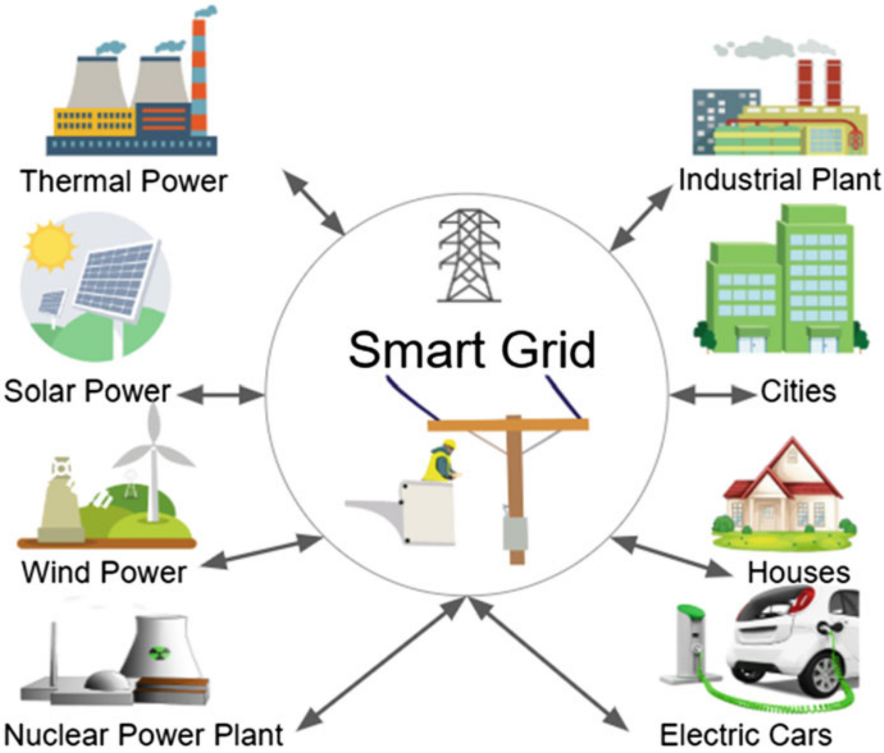


Fig. 1 Different stakeholders in a smart grid system

complex engineering system is a smart electric grid (as shown in Fig. 1), which consists of many stakeholders like energy producers (e.g., thermal power, solar power, wind power, and nuclear power), consumers (e.g., industrial plant, cities, house, and electric cars), and smart grid operators and distributors, who often independently make decisions. For energy producers, their decisions aim to achieve a profitable, sustainable power system with low losses and high levels of quality and security of supply and safety but can have repercussions on many other stakeholders. When the smart grid increases electricity price, consumers' consumption patterns may change, which in turn affects the price as well as the need for energy storage and load balancing. Hence, to make rational and optimal system-level decisions such as the price of electricity, there is a need for understanding the market demand from customers, market competition among producers, and the social and institutional environment (e.g., incentive and subsidiaries from the government).

As the observed dynamics in engineering systems result from the decision-making activities among diverse stakeholders, there is a need for modelling, analysing, and estimating the decision-making preferences of individual stakeholders in engineering systems design (Fig. 2).

Another example of an engineering system, where there is a need for considering complex multi-stakeholder interactions, is the design of electric vehicles (EVs). EVs

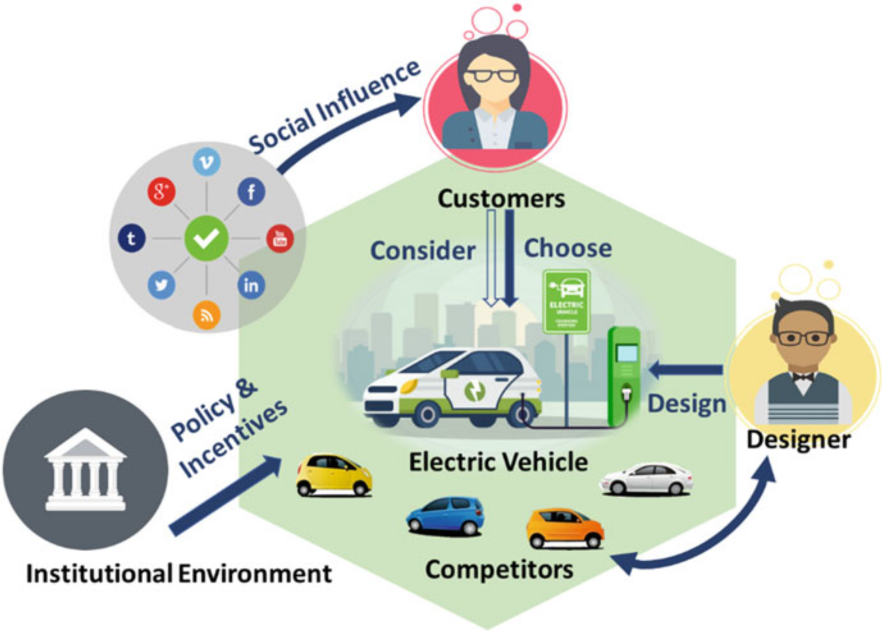


Fig. 2 The ecosystem of an electric vehicle market with different stakeholders

have emerged as competitors of traditional vehicles and other alternative fuel vehicles in the market. Like smart grids, the EV market system (as shown in Fig. 2) is also complex, with many interactions between stakeholders. Not only does the success of a new EV depend on its engineering performance, but it also hinges on how competitive the product is relative to its peers and factors like perceived market position. Customers from different geographies may prefer different types of EVs, while a design intervention in the EV market, either by introducing changes in existing EVs or by launching a new design of EV, may encourage customers to change their driving behaviour. Adding to this complexity is the need for considering heterogeneity in customers, characterised by differences in anthropometric and demographic attributes, usage context (whether they engage in highway vs. local driving), their regions (whether they are from rural or urban areas), and their socio-economic condition. Many of these factors may affect a customer's preference. While designing an EV, decision-makers must consider heterogeneous customer preferences while optimising engineering and economic factors like range/number of battery cells, vehicle weight, and price. Social and institutional environments (e.g., government subsidies) also play a critical role in both EV design and their demand among customers. For instance, the government may introduce subsidies for EVs, which may significantly reduce the total cost for consumers choosing an EV over a traditional car. Environmentally conscious customers may also consider buying EVs due to their "green attitude" or due to influence from their "social network". Similar interactions among multiple stakeholders as explained in the above two examples can also be observed in other engineering systems such as healthcare delivery, aerospace systems, global communication systems, transportation systems (like air transportation and smart urban systems), and product development process as a whole.

In this chapter, we will discuss data-driven multi-stakeholder decisions in engineering systems design, with a special focus on customer demand modelling, where customer demand and preferences play an important role. In section "Methods for Multi-Stakeholder Decision-Making", we provide a broad overview of the methods for multi-stakeholder decision-making. Section "Enterprise-Driven Decision-Based Design" covers many challenges including a paradox in multi-stakeholder modelling and discusses a rigorous enterprise-driven decision-based design (DBD) approach which illustrates the critical role of customer preference modelling. Section "Overview of Customer Preference Modelling" provides an overview of customer preference modelling, which then leads to a discussion on the random utility-based customer preference modelling in section "Random Utility-Based Customer Preference Modelling". Section "Network-Based Customer Preference Modeling" elaborates on network-based customer preference modelling approaches and how it overcomes many issues discussed in previous sections. This is followed by two case studies in section "Applications of Network Modelling for the Chinese Automotive Market" on applications of network modelling for the automotive market. Section "Conclusion and Outlook" concludes the chapter with a discussion on methods for multi-stakeholder modelling.

Methods for Multi-Stakeholder Decision-Making

While multi-stakeholder decision-making is prevalent in both engineering and non-engineering domains, there is no unified theory or framework to support the design of engineering systems that takes into consideration multi-stakeholder decision-making. There have been a few attempts at developing such a theoretical ground (Dowling et al. 2016; Kambiz 2016; Samson et al. 2018); however, these studies are outside of the engineering systems design literature. In this section, we first provide the literature of several widely examined approaches in engineering systems design – **multicriteria decision analysis**, **game-theoretic approach**, and **agent-based modelling –** and then disclose the paradox and limitations associated with these existing methods.

Multicriteria decision-making or multicriteria decision analysis explicitly evaluates multiple conflicting criteria in decision-making using approaches like Pareto optimality in operation research (Van Den Honert and Lootsma 1997) and multi-attribute utility analysis (Thurston 1990) rooted in decision theory. In contrast to engineering analysis, which is *descriptive* based on physics-based modelling, utility analysis in decision theory is a *prescriptive* or *normative* modelling tool that prescribes decision-maker's preference. Decision theory first postulates a set of "axioms of rational behavior" (Von Neumann et al. 2007). From these axioms, it builds mathematical models of decision-maker's *preference* in the form of "utility" to identify the option that would be chosen assuming that a decision-maker is consistent, rational, and unbiased. In the seminal work of Keeney (1976), it is shown that based on certain assumptions, a *group cardinal utility function* can be constructed as a linear combination of the *individual cardinal utility functions* to evaluate each decision alternative. Six assumptions (axioms) are postulated to constitute a complete, operational, decomposable, non-redundant, and minimal full set of attributes as the input of the objective or value function.

While multicriteria decision analysis has been widely used in both single designer decisions (Thurston 1991) and multi-stakeholder decisions, such as in water resource management (Hämäläinen et al. 2001), environmental decisions (Hajkowicz 2008), and urban water supply (Kodikara et al. 2010), etc., it is important to be aware of the **paradox** associated with multi-stakeholder decisions or multicriteria alternative selection/ranking processes (Saari 2000, 2006). Here we provide an example where one of the six "axioms of rational behavior" is violated. The transitivity axiom states that a decision-maker's rank ordering of preferences should be transitive: if $X \succ Y$ and $Y \succ Z$, then $X \succ Z$, where " $\succ$ " symbolises "is preferred to". Table 1 shows the preferences of three decision-makers (stakeholders) over a set of three alternatives A, B, and C. Each decision-maker is transitive. However, pairwise comparisons of the alternatives (in each column) reveal that the transitive decision-makers together as a group prefer A to B, B to C, and C to A (i.e., $A \succ B \succ C \succ A$), which is intransitive. This paradox is known as Condorcet's voting paradox. It is noted that while the paradox demonstrated in Table 1 employs multiple decision-makers (stakeholders) to reach an overall group preference, the paradox is equally applicable to using multiple design criteria to select an overall preferred design by a single designer. A similar paradox is associated with the use of weighted sum methods and other multiattribute ranking methods when more than two attributes are considered or more than two decision-makers are involved. The same paradox associated with designers' decision-making also applies to aggregate the preferences of customers by treating them as a group.

In multi-stakeholder decision-making, the competition and collaboration among stakeholders (players) have been addressed in design research and systems engineering using the game-theoretic approach (Dutta and Dutta 1999; Von Neumann et al. 2007). Game theory is the study of mathematical models of strategic interaction among rational decision-makers. It has applications in many fields of social science, as well as in logic, systems science, and computer science. In engineering design, a game-theoretic approach has been used by Lewis et al. (REF) to model multiple types of interactions in multidisciplinary design by abstracting them as a sequence of

Table 1 Multi-stakeholders voting paradox

Preferences	A vs. B	B vs. C	C vs. A
Decision-maker I ($A \succ B \succ C$)	A	B	A
Decision-maker II ($C \succ A \succ B$)	A	C	C
Decision-maker III ($B \succ C \succ A$)	B	B	C
Group preference	$A \succ B$	$B \succ C$	$C \succ A$

games among a set of players (disciplines, e.g., structure, aerodynamics, and control in aircraft design) using three different game protocols (Pareto, Nash, and Stackelberg, YEAR) (Lewis and Mistree 1997). However, Grogan and Meijer (2017) view engineering systems research to consider not only the technical design of a system but also the bidirectional effects it has on the encompassing social system. A comprehensive review of the game theory models in engineering systems and its applications was provided in their paper. To build meaningful game-theoretic models to model decision interactions, Sha et al. illustrate how the analytical game-theoretic models and behavioural experimentation can be synergistically used to gain a better understanding of decision interactions using an example of crowdsourcing as the demonstration of engineering design under competition (Sha et al. 2015). In the market system, game-theoretic models have been used to study the enterprise decision-making in the presence of multiple competitors. These studies generally go in three directions: (a) pricing strategy (Shiau and Michalek 2009), (b) design configuration decisions in either single product design (Kaul and Rao 1995) or product line design (Jiao and Zhang 2005; Liu et al. 2017), and (c) strategic decisions on product innovation (Kato et al. 2013). For example, Liu et al. used a Stackelberg-Nash game to study the interaction between a new entrant (leader) and incumbent firms (followers) when this new entrant plans to offer a new product configuration, but existing products belong to several incumbent firms.

In a complex design ecosystem like the two examples shown in section “Introduction”, the dynamic interactions between multiple competitors in the market cannot be ignored. However, existing game-theoretic approaches (e.g., often in a setting of two-player games) cannot model interactive decisions among a large number of competitors. To study relational dynamics, many network-based models, such as the small-world model (Watts and Strogatz 1998), the Barabási-Albert model (Barabási and Albert 1999), and the dynamic stochastic block model (Xu and Hero 2013), were proposed in network research. Yet, they are primarily developed based on network metrics solely, e.g., node degree (the number of connectivity) and clustering coefficient, and do not take into account the exogenous attributes of the nodes. Hence these stylised models do not offer ways of relating engineering design attributes (engineering design decisions) to the evolution of competition network, making them of little direct value to engineering design.

Aside from the normative utility analysis approach and the semi-normative game-theoretic approach, **agent-based modelling (ABM)** offers a simulation approach in which individual entities (a collection of autonomous decision-making entities) individually assess their local situations and make decisions based on a set of rules (Bonabeau 2002). Agents that represent different stakeholders can possess different strategies for responding to the actions of other agents and the dynamic environment of the system. In addition, agent-based modelling (ABM) has been employed for examining the influence of various policies with regard to how they dictate human behaviour and the sometimes unanticipated patterns that arise from the collective behaviour (often known as *emergence* (Bar-Yam 2002)). While the agent-based modelling (ABM) approach is powerful to consider heterogeneous behaviour of multiple stakeholders in engineering systems such as power grid (Ramchurn et al.

2011), forest management (Bone and Dragićević 2010), and city logistics (Anand et al. 2016), the behaviour models of individual entities in the system need to be known a priori and precisely specified; hence calibration and validation of such models is always a challenge.

Enterprise-Driven Decision-Based Design

To overcome the aforementioned limitations of existing methods and address the challenges of multi-stakeholder decision-making, we present in this section an **enterprise-driven decision-based design** (DBD) approach (Chen et al. 2013) to support engineering design decisions. Based on the principles of decision theory (Keeney and Raiffa 1993), DBD is a collaborative design approach that employs a single value function (e.g., profit) from the enterprise's perspective to maximise the expected utility of a designed artefact while also considering uncertainty and the decision-maker's risk attitude. The approach is rational because it avoids the paradox associated with the multiattribute utility function by using a single criterion (e.g., profit) from the enterprise's perspective and models the market competitions through customer preference models in which multiple product alternatives considered by each customer are modelled explicitly. The selected single criterion reflects the many different aspects involved in engineering design, such as product features, manufacturing considerations, and physical restrictions imposed by engineering disciplines as well as customer preferences. In essence, it is a rational design approach that *enables a designer to make optimal decisions considering both the designer preference and customer preferences, as well as the collective effect of dynamics from different entities and interrelations in a design ecosystem*.

As shown in Fig. 3, the core of the enterprise-driven decision-based design (DBD) is the use of demand modelling (Chen et al. 2013) to estimate the effect of design changes on a product's market share, aggregated from individual customers' choice probabilities and consequently on the firm's revenues. It is the inclusion of consumer choice modelling that differentiates enterprise-driven design problems from other design research. As shown in Fig. 3, product demand Q plays a critical

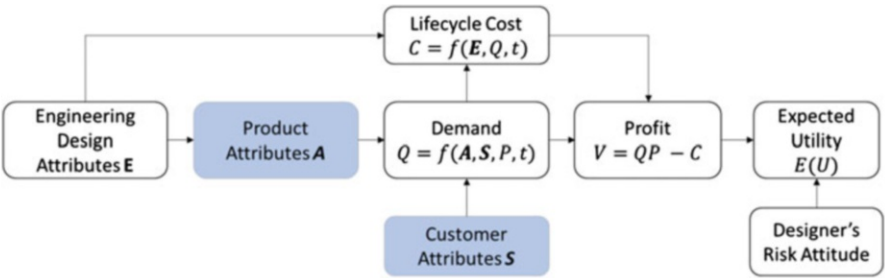


Fig. 3 Role of customer preference (demand) modelling in enterprise-driven design

role in assessing both the revenue and life cycle cost C and ultimately the profit (i.e., net revenue) V. Demand Q is expressed as a function of the product attributes A (i.e., what product attributes, including incentives, do customers care about), customer attributes S (i.e., demographics, usage context, green attitude), price P, and time t. By relating attributes A to engineering design attributes E, the optimal level of E can be identified through maximising the *expected value of profit E(U)* (a.k.a. expected utility in utility optimisation) to guide engineering design or system development.

Under the enterprise-driven design framework, designer preference is represented by an enterprise design objective (the net revenue V) and the associated risk attitude, and customer preferences are captured through demand prediction. **Customer preference modelling**, as the backbone of the enterprise-driven design, emphasises understanding how customers make trade-offs among multiple attributes when making consideration (i.e., what options to consider) and purchase decisions (Chen et al. 2015; Doondelinger and Ferguson 2017; Du and MacDonald 2015; Wang and Chen 2015; Wassenaar and Chen 2003, p. 20). The ability to accurately and reliably model the heterogeneity in customer preferences can help enterprises design products that are not only profitable but also more likely to satisfy a broader range of consumers (i.e., increased market share) (Kumar et al. 2009c). Existing literature has demonstrated that customer preference modelling can support engineering design in many aspects, including conceptual design (Hoyle and Chen 2009), multidisciplinary design (MacDonald et al. 2009), product configuration (Sha et al. 2017), product innovation (Chang and Chen 2014; Chen et al. 2015), and design accounting for spatiotemporal heterogeneities (Bi et al. 2018). More details of customer preference models are introduced next.

Overview of Customer Preference Modelling

While customer needs analysis focuses on identifying desired features/attributes and functionalities of a product (Clarkson et al. 2013; Norman 1988, 2004), **customer preference modelling** emphasises understanding how customers make trade-offs among multiple attributes when making purchase decisions. Analytical modelling of customer preferences as a function of product attributes and customer attributes is essential for bridging the gap between market research and engineering design research (Chen et al. 2013; Kim et al. 2006; Kumar et al. 2006; Ross Morrow et al. 2014) as explained in the enterprise-driven design framework presented previously in section “Methods for Multi-Stakeholder Decision-Making”. The review article by Doondelinger and Ferguson (2017) states that engineering design research has increasingly incorporated representations of preference as a means of addressing market-driven design decisions. In market-driven design, customer preference models have been used to estimate **demand**, aggregated from individual customers’ choice probabilities and the total market size, to assess both the production cost and design revenue. Customer preference models facilitate engineering design in many aspects, including design attributes selection (Hoyle and Chen 2009), usage and social context-based design (He et al. 2012), multidisciplinary design (MacDonald et al. 2009), product configuration (Sha et al. 2017), and design of engineering systems (Kumar et al. 2009a, b; Michalek et al. 2006; Sha et al. 2016; Sha and Panchal 2014). The most common procedures of customer preference modelling involve **data collection** and **demand modelling**, which are explained next.

Overview of Data Collection Techniques

Two main types of data are primarily used to model demand: **stated preference (SP)** data (Louviere et al. 2000) and **revealed preference (RP)** data. Revealed preference (RP) data refers to actual choice, i.e., it can be verified that a customer purchased a product in the real. In contrast, collecting data on stated preference (SP) often requires controlled choice experiments that ask the respondents to state their purchase intent. Surveys are typically used to learn about how people are likely to respond to new products or new product features. SP data is often used in conjoint analysis-based modelling, while RP data is usually associated with modelling methods like discrete choice analysis, which are quite common in transportation and economic applications. In the marketing and transportation research literature, conjoint analysis is a frequently applied SP research technique, which encompasses the analysis of three types of consumer preference data: ratings, rankings, and choice data (Ben-Akiva et al. 1992; Bradley and Lang 1994; Haaijer et al. 1998; Louviere et al. 1993). With stated choice, the survey respondent is asked to pick an alternative from a choice set in a process very similar to real purchase decisions. A choice set contains a number of competing alternatives: a "survey alternative" (i.e., a new product or the alternative with the improved design), one or more competing alternatives from competitors, and sometimes a "no choice" alternative (i.e., not to purchase anything). The alternatives are described by the customer-desired attributes (A), including important business aspects such as price and warranty. The choice sets can be generated using design of experiment techniques. The survey results (choice data) are recorded, along with the respondent's customer background (S) such as age, income, product usage, etc.

The differences between revealed preference (RP) and stated preference (SP) are listed in Table 2. Both stated choice and revealed choice have advantages and disadvantages (Louviere et al. 2000). Limitations of revealed choice are that it is not always clear what choice alternatives were available to the customer at the time of purchase. Stated choice, on the other hand, is a controlled choice experiment, where alternatives, the attributes, and the attribute levels are controlled by the researcher and explicitly known to the respondent. However, a limitation of stated choice is that respondents do not need to commit to their choices (e.g., pay the purchase price), which can result in a mismatch between what respondents say they will do and purchases they would make if they have to commit. Additionally, the respondent is typically asked to respond at that might mention by themselves without having time to reflect or to discuss with others. Hence, they may not analyse all attributes and competing products while providing stated choice data, or they may

Table 2 Comparison of revealed preference (RP) and stated preference (SP) data (Adapted from (Train 2009))

Revealed preference data	Stated preference data
Based on actual market behaviour	Based on hypothetical scenarios
Attribute measurement error	Attribute framing error
Limited attribute range	Extended attribute range
Attributes correlated	Attributes uncorrelated by design
Hard to measure intangibles	Intangibles can be incorporated
Cannot directly predict response to new alternative	Can elicit preferences for new alternatives
Preference indicator is choice	Preference indicators can be rank, rating, or choice intention
Cognitively congruent with market demand behaviour	May be cognitively non-congruent

use different attributes in their response, compared to a real-life purchase decision. Besides, not every competing product may be available to the respondent in a real purchase situation. Generally, revealed choice is used when similar products or services exist, e.g., when redesigning a power tool, while stated choice is used for innovative new designs, product features, or services that do not yet exist. The relative merits and demerits are tabulated below.

In recent years, more advanced techniques have been developed to overcome the difficulties in dealing with both stated preference and revealed preference. Associated with preference elicitation is the issue of survey (experiments) design to best collect the data needed for the preference modelling. To avoid respondent fatigue, Hoyle et al. (Hoyle et al. 2009) developed an algorithm to identify the optimal design for the human appraisal experiment. To reduce survey length, Chen et al. (Chen et al. 2012) proposed an approach to resemble efficient Global optimisation that creates questions using feedback from prior responses. A query algorithm has also been introduced that updates the user preference model during data collection (Akai et al. 2010) allowing for survey length reductions by querying preferred designs from previous users with a similar preference structure. In addition, it is increasingly recognised that big data will be a key foundation supporting product improvement, product redesign, and product innovation (Sawhney et al. 2005). This trend requires researchers to develop new technologies to integrate, analyse, visualise, and use the growing torrent of big data. While market survey data of customer consideration sets and choices are often difficult to obtain, open data (Parraguez and Maier 2017), which refers to data that can be freely used, reused, and redistributed by anyone, has created more opportunities for research in engineering design. The spread of Web 2.0 has led to a colossal quantity of information posted online in social media such as forums, blogs, and product reviews. Exploiting the online platform, the crowdsourced design has been introduced (Gerth et al. 2012), enabling customers to contribute direct evaluations of perceptual design attributes. Recent studies also explore the potential of online customer reviews and opinions to facilitate engineering design via product design features detection (Rai 2012) and product design selection (Wang et al. 2011). Various machine learning approaches have been explored that are capable of mining transactional data for hidden purchasing patterns. This includes data mining techniques for creating new choice modelling scenarios (Wang et al. 2016a), exploring the viability of Twitter as a source for product opinions (Stone and Choi 2013), yielding high-accuracy predictions of preference (Burnap et al. 2016), and creating market segments from online reviews focused on individual product attributes and identifying attribute importance rankings (Rai 2012). Furthermore, rather than treating stated preference (SP) and revealed preference (RP) as competing valuation techniques, analysts have begun to view them as complementary, where the strengths of each type can be used to provide more precise and possibly more accurate models, and this approach is better known as data enrichment or model fusion in the literature (Mark and Swait 2004; Merino-Castello 2003).

In addition to collecting data on stated or revealed preferences, **desired/key features/attributes** and functionalities also need to be treated as explanatory variables in preference modelling. Tucker and Kim (Chen et al. 2012) proposed the preference trend mining algorithm to help detect the unobservable customer preference trend using data mining techniques, hence enabling design engineers to anticipate the next generation of product features. Van Horn (Van Horn et al. 2012) expanded the design analytics concept and demonstrated the effective usage of information-to-knowledge transformations from data analytics at every design stage. In addition, customer heterogeneity needs to be modelled by introducing customer attributes, such as demographic attributes, usage context, green attitude, etc. as inputs in demand modelling.

Overview of Demand Modelling Techniques

Early work in analytically modelling customer preference can be traced back to market research, where various analytical methods such as multiple discriminant analysis (Johnson 2011), factor analysis (Gorsuch 1983), multidimensional scaling (Green 1970), conjoint analysis (Green and Krieger 1991; Green and Srinivasan 1978, 1990; Green and Tull 1970; Green and Wind 1975), and discrete choice analysis (DCA) (Ben-Akiva and Lerman 1985; Train 1986, 2009) were developed. Methods for modelling customer preference can be divided into two main categories: the *disaggregate* approaches, which use data of individual customers, and the *aggregate* approaches, which use group averages and model market share as a function of the characteristics of the alternatives and socio-demographic attributes of the group of customers. Disaggregate approaches explain why an individual makes a choice given her/his preference and, therefore, better reveal the changes in heterogeneous customers' choice behaviours due to the changes of individuals' characteristics and the attributes of products.

In addition to the aforementioned earlier techniques, existing analytical preference models also include value-based models (Cook and DeVor 1991), agent-based models (Zhang et al. 2011), and network-based models (Wang et al. 2015, 2016a, b). Among value-based models, the most widely used technique for modelling customer preferences has been primarily based on random utility theory (Chen et al. 2013), which assumes that a customer's choice is made by comparing the unobserved utilities, expressed as functions of product attributes of competing design alternatives as well as customer attributes. Particularly, the **discrete choice analysis** (DCA) (Train 1986) and conjoint analysis (Tovares et al. 2013) have been widely employed by the design research community (Frischknecht et al. 2010; He et al. 2014; Hoyle et al. 2010). In the following section "Methods for Multi-Stakeholder Decision-Making", we will examine more closely utility-based preference modelling, highlighting their advantages and disadvantages. To overcome the limitations of these random utility-based choice modelling techniques, recent developments of **network modelling techniques** will be introduced in sections "Network-Based Customer Preference Modelling" and "Applications of Network Modelling for the Chinese Automotive Market" along with examples.

Random Utility-Based Customer Preference Modelling

Discrete choice analysis (DCA) is rooted in economics but later extended to the fields of transportation research (Ben-Akiva and Lerman 1985; Sha et al. 2016), engineering design (Sha et al. 2017), systems engineering (Chen et al. 2013; Sha and Panchal 2014), and many other fields to meet the needs of estimating individual preferences and system (market) demand in general. It should be noted that statistical analysis (Box and Tiao 2011; Green et al. 1976; Johnson and Wichern 2002; Neter et al. 1996) and data mining/machine learning techniques (Bishop 2006; Witten and Frank 2002) also have a long history of use in market research (Allenby and Rossi 1998; Berry 2004; Lilien et al. 1995) and engineering design (Chen et al. 2012; Malak and Paredis 2010; Ren and Papalambros 2011; Tucker and Kim 2008, 2009, 2011; Wang et al. 2011) for analysing customer preferences. However, most of those techniques are *aggregate approaches* that divide customers into groups sharing similar needs and preferences (Kaul and Rao 1995), such as multiple discriminant analysis (Johnson 2011), factor analysis (Gorsuch 1983), and multidimensional scaling (Green 1970). Consequently, aggregate models are more appropriate for modelling group preference instead of individual customer's preference.

The fundamental part of the utility-based approach relies on the formulation of the utility function. In DCA, a decision-maker obtains utility U_i from choosing an alternative i, which consists of two parts, the observed utility V_i, which is deterministic from the researcher's point of view, and the unobserved utility ε_i representing all possible uncertainties associated with the utility, such as unobserved variations, measurement errors, and functional misspecifications. This can be modelled as

$$U_i = V_i + \varepsilon_i. \tag{1}$$

In a DCA, V is modelled as a function of explanatory variables, typically represented in a linear additive form (Ben-Akiva and Lerman 1985), as shown in Eq. (2).

$$V_i = \boldsymbol{x_i}\boldsymbol{\beta_i^T} = \beta_{i1}x_{i1} + \beta_{i2}x_{i2} + \ldots + \beta_{ik}x_{ik}, \tag{2}$$

where $\boldsymbol{x_i} = (x_{i1}, x_{i2}, \ldots, x_{in})$ is a vector that contains n variables and $\boldsymbol{\beta_i} = (\beta_{i1}, \beta_{i2}, \ldots, \beta_{in})$ is the vector of model parameters that quantify preferences in choice making. The DCA is derived based on random utility maximisation, meaning that the alternative i is chosen rather than j if, and only if, $U_i \geq U_j, \forall i \neq j$. So the choice probability of alternative i is

$$P_i = P\left(U_i \geq U_j\right) = P\left(V_i - V_j \geq \varepsilon_j - \varepsilon_i\right) \forall i \neq j. \tag{3}$$

Equation (3) can be solved as soon as the density function $f(\varepsilon)$ is specified because P_i is the cumulative distribution of $\varepsilon_j - \varepsilon_i$. With different $f(\varepsilon)$, various DCA models can be obtained, such as the probit model if assuming that ε follows the Gaussian distribution or the logit model if ε is identical independent distributed following the Gumbel distribution (Ben-Akiva and Lerman 1985). With the later distribution assumption, the model in the scenario where one alternative is chosen from multiple alternatives is called multinomial logit model, as shown in Eq. (4):

$$P_i = \frac{e^{x_i\beta_i^T}}{\sum_{j=1}^{J} e^{x_j\beta_j^T}}. \tag{4}$$

In addition to the multinomial logit model, a variety of discrete choice analysis (DCA) models, such as nested-logit (Kumar et al. 2009a) and mixed logit (Hoyle et al. 2010), have been developed to capture the system heterogeneity by introducing customer attributes as model inputs and random heterogeneity among individuals through random coefficients. Even if the utility-based approach provides a sound framework for modelling customer preferences, several major roadblocks are impeding their use in practical design applications:

(a) *Dependency*. Standard logit models in DCA ignore correlations in unobserved factors over product alternatives by assuming observations are independent, i.e., whether a customer chooses one product is not influenced by adding or substituting another product in the choice set, which is often not a realistic situation.
(b) *Rationality*. The utility function assumes customers make rational and independent decisions. However, in reality, customers' decisions influence each other, and their socially influenced decisions can sometimes be considered "irrational".
(c) *Collinearity*. The utility-based approach which relies on regression techniques is difficult in handling collinearity of design attributes, e.g., vehicles with low prices are more possible to have smaller engine capacity (Wang et al. 2016b).

(d) *Choice set*. When choice set data is not available, misspecification of choice sets can result in inferior choice model estimates (Shocker et al. 1991; Williams and de Ortúzar 1982), especially when a large set of choice alternatives exist for a product.

To overcome these limitations, a few studies have begun exploring the capability of statistical network models in estimating customer preferences (Fu et al. 2017; Sha et al. 2018). Among existing network-based modelling techniques, the exponential random graph model (ERGM) is increasingly recognised as particularly promising (Snijders et al. 2006). ERGM provides a flexible statistical inference framework that can model the influence of both exogenous effects (e.g., nodal attributes) and endogenous effects (network structures/nodal relations) on the probability of connections among nodes. ERGM has been used to study customers' consideration behaviours (Sha et al. 2017), forecast the impact of technological changes on market competitions (Wang et al. 2016b), model customers' consideration-then-choice behaviours (Fu et al. 2018), and predict products' co-consideration relations (Sha et al. 2018; Wang et al. 2018). In the following section, more details of network-based modelling of customer preferences are introduced.

Network-Based Customer Preference Modelling

Network analysis has emerged as a key method for statistical analysis of engineering systems in a wide variety of scientific, social, and engineering domains (Albert et al. 2000; Braha et al. 2006; Holling 2001; Hoyle et al. 2010; Newman 2003; Simon 1977; Wasserman and Faust 1994). The premise underlying the network-based approach is that, similar to other engineering systems exhibiting dynamic, uncertain, and emerging behaviours, customer-product relations can be viewed as a complex socio-technical system and analysed using **social network theories and techniques** (Chen et al. 2018). The structural and topological characteristics identified in customer-product networks can help reveal patterns in the customer-product relations while also modeling the heterogeneities in customers and products.

Motivation for Using Complex Networks for Modelling Customer Preferences

As discussed in section "Overview of Customer Preference Modelling", modelling customer preferences using traditional methods faces many major challenges. There are large uncertainties associated with customers' decision-making processes influenced by the market (e.g., the demand), society (e.g., social norms), and technology development (e.g., technology innovation) factors. With the growth of social media, such uncertainties are further compounded with new forms of social interactions (Brock and Durlauf 2001), such as online reviews. Moreover, the complex decision-making process itself poses a challenge, where consumer research (Hauser et al. 2010; Hauser

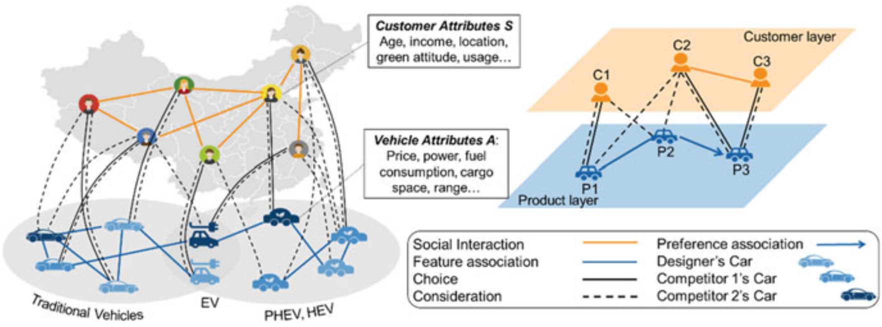


Fig. 4 **An illustration of the multidimensional network for** customers-vehicle relations. Left: the figure illustrates the customer-product relations from a multidimensional network perspective. This network has two layers: the product layer and the customer layer. The product layer contains a collection of engineering products (e.g., vehicles), and the customer layer consists of customers who make consideration and purchase decisions. In total, the network consists of two types of nodes and five possible types of links (relations). Right: the multidimensional customer-product network (MCPN) figure illustrates a graphical simplification, denoting customers as orange human icons and products as blue car icons

and Wernerfelt 1990; Shao 2007; Shocker et al. 1991) indicates that customers' decision-making process may consist of multiple stages. Figure 4 illustrates the two stages of decision-making in the process of car purchase – consideration and then choice. Other challenges exist in modelling heterogeneous human behaviours, complex human interactions, and a large variety of product offerings.

In recent work, Sha et al. (2019) compared the network-based approaches with the utility-based approaches for choice prediction and found that a network-based statistical model provides consistent results and the same factor effects as discrete choice analysis method when only exogenous variables are considered. This finding provides support to the argument that statistical methods for network modelling provide a more generalised framework that subsumes the utility-based approach but is in addition capable of modelling complex endogenous relations in the design ecosystem not captured by utility-based approach. In this section, we discuss how the customer preference modelling can be cast as network modelling of the customer-product relations. Specifically, we will show how the limitations of the existing utility-based choice models in modelling complex customer-product relations can be addressed. The approach also enables visualisation of complex relationships by using network graphs, where nodes represent individual members and ties/links represent relationships between members.

Multidimensional Customer-Product Network

In the social network domain, researchers have emphasised the development of multidimensional networks (Contractor et al. 2011), which includes multiple types of nodes, as well as multiple types of relations represented by non-directed or directed links between nodes of the same or different types. When one thinks about modelling customer choice using networks, a heterogeneous set of stakeholders and relationships come to mind. Hence, we discuss a multidimensional framework for customer preference modelling, as shown in Fig. 4, which is called the MCPN (multidimensional customer-product network) framework. In the MCPN framework, two classes of nodes exist at two layers ("product" and "customer"), and multiple types of relations are within and between those two layers. The product layer contains a collection of engineering products (e.g., vehicles). Products are connected by various links, which can be either directed or non-directed. Directed links may represent product hierarchy or preference, while non-directed links may represent product similarity or association. Product attributes or features, quantitative (e.g., fuel efficiency, horsepower) or qualitative (e.g., safety, styling), can be considered as node attributes. Similar attributes/features between products are represented as association links in the product network.

The customer layer describes a network consisting of a nodes representing people who make decisions or take actions regarding car purchase. Each customer has a set of node attributes such as socio-economic and anthropometric attributes, purchase history and usage context attributes, etc., which potentially affects their preference and decisions. Links between two nodes may represent the relationship betweeen customers such as social relations. The structural tendencies of these social relations reflect the underlying multi-theoretical multilevel social processes for creating and maintaining links such as homophily (when an entity has ties with other entities which are similar to it) and proximity (when an entity has ties with other entities which are closer to it) (Monge and Contractor 2003). Customer-product relations are indicated by various human activities such as purchase and consideration decisions. The customer-product links are created between two sets of nodes from two adjacent layers, representing those decision activities. As shown in Fig. 4 (left), if a customer purchases a product, there is a solid line linking the customer and product nodes. If a customer considers purchasing a product, the link between the two nodes is marked as a dashed line.

Note that a few DCA models also extend single decision processes (i.e., choosing from a fixed set of alternatives) to multiple decision-making stages, such as consideration-then-choose models (Ross Morrow et al. 2014), individual choice set models (Wang and Chen 2015), and hierarchical Bayesian models (Shin and Ferguson 2017). These studies found that choice modelling in multiple decision stages led to a better prediction of market shares and improved engineering design decisions. In these studies, two strategies have been proposed and generalised for capturing customer preferences in the consideration set formation: (1) rule-based heuristics such as the "satisficing" strategy in (Hastie and Dawes 2009) used by customers to screen and select a set of good enough alternatives with must-have features for further consideration and (2) parametric models to directly reflect product preferences (Swait 2001). While both methods can model attribute main effects and attributes interaction effects, the network model has the unique capability of modelling network effects like homophily, the effects of endogenous variables such as the edge effect representing network density, the star effect, the cross-level association-based closure effect, and the cross-level “peer influence” to be illustrated in the case study in section “Network-Based Customer Preference Modelling”.

The MCPN model in Fig. 4 can be modified to represent models of customer preference in different levels of complexity. For example, it has the flexibility of being a one-mode (unidimensional) network defined within one layer (either product or customer), a bipartite (two-mode) network defined between nodes from two levels, or a multidimensional network that has links between two levels or within a level. These network configurations capture the interdependency among links as well as between attributes of links and nodes to represent complex behaviour patterns. These patterns stem from complex underlying social processes such as self-interest, collective action, social exchange, balance, homophily, contagion, and coevolution (Contractor et al. 2011).

Descriptive Network Analysis

Descriptive network analysis can provide many insights into a system. For example, Wang et al. (2016a) created a unidimensional network of cars and found that Audi FAW Q5 and Ford Kuga are popular vehicles, indicated by their high ranks in degree centrality and in-degree hierarchy. In contrast, Volvo V40 and Ford Edge have been frequently considered when purchasing a car (high-degree centrality in an undirected network) but fall behind in customers’ final choices (low in-degree hierarchy). So, descriptive network analysis could be a valuable tool for designers to determine product positioning and product priorities in the phase of design planning.

Descriptive network analysis can be applied either in a unidimensional network or in a multidimensional network. Descriptive network analysis on multidimensional networks can provide insights into how heterogeneous systems interact, but many existing applications of network analysis are unidimensional that contain a single class of nodes (either human or non-human artefact) and a single type of relation. The unidimensional network can be viewed as a simpler version of the bipartite network, as it is obtained by projecting the customer-product network to a single node type (Wasserman and Faust 1994). A unidimensional network can also be employed to model customer preference, where aggregated customer preferences and product similarities are analysed to inform designers about the implied product competitions and market segments. An example of a unidimensional network is shown in Fig. 5a, where all nodes are of the same type.

Exponential Random Graph Model

Beyond the traditional descriptive network analysis, statistical models like the exponential random graph model (ERGM) can be employed as a unified statistical inference framework to interpret complex preference decisions. ERGMs were used to study customers’ consideration behaviours using the unidimensional network at the aggregated market level (Sha et al. 2017) and multidimensional network at the

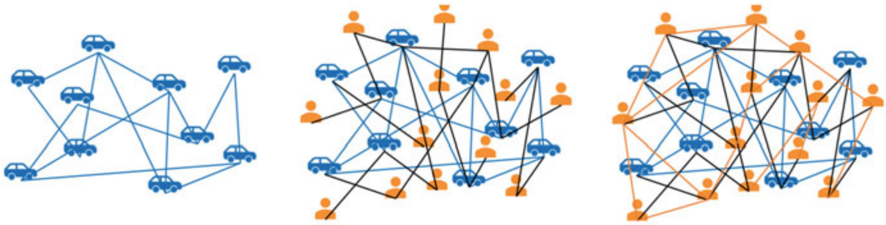


Fig. 5 Product and customer networks with increasing complexity from left to right. (**a**) Product relations only, (**b**) preference links added, (**c**) social relations added

disaggregated customer level (Wang et al. 2016a), respectively. The estimated unidimensional model was used to forecast the impact of technological changes (e.g., turbo engine) on market competition (Wang et al. 2016b), which illustrated the benefits of using the network-based preference model for design.

To use an ERGM for statistical inference, we can define matrix Y as a random graph in which rows and columns represent customers and products, respectively. $Y_{ij} = 1$ refers to a relation, such as the preference (consideration or purchase) decision between customer i and product j, and 0 otherwise. ERGM has the following form:

$$\Pr(Y = y) = \frac{\exp\left(\theta^T g(y)\right)}{\kappa(\theta)}, \tag{5}$$

where (a) y is the observed network, a random realisation of Y; (ii) $g(y)$ is a vector of network statistics corresponding to network characteristics in y and the settings of product and consumer attributes; (iii) θ is a parameter vector indicating the effects of the network statistics; and (iv) κ is the normalising constant that ensures the equation is a proper probability distribution. Eq. (5) suggests that the probability of observing any particular graph (e.g., MCPN) is proportional to the exponent of a weighted combination of network characteristics: one statistic $g(y)$ is more likely to occur if the corresponding θ is positive.

ERGMs have **several** advantages over the utility-based logit models as noted in Wang et al. (2016a):

1. Network links are modelled to be interdependent in ERGM rather than assumed to be independent.
2. ERGMs can incorporate binary, categorical, and continuous nodal attributes to determine whether they are associated with the formation of network links.
3. ERGMs are capable of characterising local and global network features.
4. ERGMs can be applied in flexible ways to many different types of networks and relational data.
5. Data used for fitting ERGMs can be cross-sectional or longitudinal (changes with time), and a dynamic model can be built to study the emergence and dynamics of a network.

6. In contrast to a machine learning model that focuses on prediction, ERGMs are explanatory models.

Using ERGMs, one can quantify the effects of social influence by statistically estimating the extent to which structural tendencies implied by social theories influence the probabilities of the observed network.

Modelling the Effects of Network Configurations

An exponential random graph model (ERGM) can estimate the effects of many different types of network configurations (Lusher et al. 2013) to explain the observed relational data within social networks. Examples of a few configurations are provided in Table 3, which we later discuss in a case study for modelling a system. The network configurations fall into three categories: pure structural configurations, attribute-relation configurations involving product/customer attributes, and cross-level configurations involving both between-level and within-level relations. The focus of network analysis is often to interpret the meaning of these configurations to understand the customer-product relations for engineering design. Pure structural configurations are related to the well-known structural regularities in the network literature; attribute-relation configurations assume the attributes of products/customers can also influence possible tie formations in a given structure. At the dyadic or two-node level, interpretation resembles the attribute effect in a logistic regression (Strauss and Ikeda 1990; Wasserman and Pattison 1996). The main effects can be used to test how attractive a product attribute is. The interaction effects capture whether certain features influence the decision of a particular group of customers or not. Beyond conventional logistic models, the network approach also evaluates higher-order effects, such as at the levels of three-node and four-node. The product association relations can be modeled by the cross-level configurations that integrate customer preferences with product similarities. In this way, the analysis can help explain the influence of the design attribute in considering product alternatives. The interaction effects capture whether certain features influence the decision of a particular group of customers or not. Beyond conventional logistic models, the network approach also evaluates higher-order effects, such as at the levels of three-node and four-node. The product association relations can be modeled by the cross-level configurations that integrate customer preferences with product similarities. In this way, the analysis can help explain the influence of the design attribute in considering product alternatives.

Applications of Network Modelling for the Chinese Automotive Market

In the aforementioned MCPN (multidimensional customer-product network) framework, there exist two major stakeholders (“products” and “customers”) and multiple types of relations (“customer consideration”, “customer choice”, “product association", and "customer social network") within and between those players. In this section, we present two studies on customer preference modelling for the Chinese auto market as an illustration of network modelling approach to model multi-stakeholder preferences in the engineering system. The first case study investigates what vehicles people consider to buy, while the second case study is used to show how to model customer choice in buying a vehicle, given that we know which vehicles they considered. Even though our case study is focused on customer preference modelling, the same network modelling approach can be used to study the complex relations among multiple stakeholders.

Case Study 1: Using MCPN for Modelling Luxury Vehicle Preferences in Central China

We adopt a case study from Wang et al. (2016a) to show how a customer preference modelling problem can be formulated using networks. We discuss three data-driven approaches for modelling vehicle preferences in the Chinese market. This research first examines the use of unimodal networks, studying the product associations from a customer's point of view and identifying product co-considerations and preference hierarchies. Next, a multidimensional network is constructed where the exponential random graph model (ERGM) is applied for analysing customer preferences towards vehicle products while assessing simultaneously the impact of customer social interactions and product associations. We begin by explaining a three-step approach with the following steps: (1) network construction, (2) network modelling, and (3) interpretation of results, explained next.

Step 1: Network Construction Based on Survey Data

To study customer preference in what cars to consider, we first need to create a network, which correctly encodes the consideration relationships we want to study. For our example, the data was provided by an independent market research institute in China. The survey contains preferences from 49,921 new car buyers who considered and purchased from a pool of 389 vehicle models in 2013. It has information on what cars these buyers considered and what car they finally purchased. It also has customer demographics (age, location, gender, etc.) and information on the products (car mileage, price, model, engine size, etc.). In the survey, each respondent listed the car they purchased along with a maximum of two additional car models they considered (i.e., the main alternative and the second alternative). We call the set of cars a customer considered (including the one bought) as the consideration set of that customer.

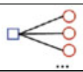
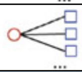
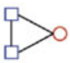
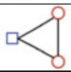
The authors in (Wang et al. 2016a) create three different networks of increasing complexity as shown in Fig. 5 by defining different types of edges and nodes. In the first network (Fig. 5a), individual cars are defined as the blue-coloured nodes in the network. Edges between a car i and a car j are defined as the number of customers who considered both cars together in their consideration set. In Fig. 5b, customer nodes are also introduced in the network, and there is a link between a customer and all the cars considered by them. Finally, in Fig. 5c, the third type of edge is added between customers, based on how similar they are from each other to mimic social influence.

Step 2: Network Modelling

Three different ERGMs, with increasing complexity, are studied in this case study. To train an ERGM, the network and also the attributes are first defined. The attributes are typically node attributes, edge attributes, or network attributes. Table 3 shows the attributes considered for each model in the study. The significant coefficient estimates are shown in bold font, meaning that the corresponding configurations are significant at the 95% confidence interval.

By comparing the three models, one can gain many insights about customer choice behaviour and product competition. Model 1 formulates a bipartite ERGM analogous to a logistic model that contains only the attribute-relation effects composed by attributes of customers and products. This model allows the testing of influencing customer/product attributes in customer preference decisions, assuming

Table 3 Comparison of three specifications of ERGMs. For each considered network effect, the graphical configuration z(y) is presented accompanied by the estimated coefficient (θ) and the standard error. Blue squares here represent vehicles and red circles are customers

		Model 1		Model 2		Model 3	
Configurations	Interpreted effects	Est. coeff.	(Std. err.)	Est. Coeff.	(Std. err.)	Est. Coeff.	(Std. err.)
Pure Structure effect							
	Density	**-7.0314**	**(0.398)**	**-9.1009**	**(0.495)**	**-8.9648**	**(0.477)**
	Product popularity			**6.4996**	**(0.644)**	**6.5123**	**(0.631)**
	Consideration range			**-1.4036**	**(0.516)**	**-1.3199**	**(0.522)**
Attribute-relation main effect							
	Price paid to the dealer (in 100K RMB)	**-0.0346**	**(0.020)**	-0.0194	(0.019)	-0.0182	(0.018)
	Turbocharger (dummy)	**1.2796**	**(0.109)**	**1.0617**	**(0.122)**	**0.9056**	**(0.118)**
	Engine capacity (in cc)	**0.2809**	**(0.134)**	0.2356	(0.129)	0.1871	(0.119)
	Fuel consumption (in L/100 km)	0.1581	(0.039)	0.1270	(0.036)	0.1162	(0.035)
	First-time buyer (dummy)	**-0.2343**	**(0.096)**	**-0.9745**	**(0.215)**	**-0.9744**	**(0.214)**
	Monthly household income (in 100K RMB)	0.0027	(0.002)	0.0102	(0.003)	**0.0125**	**(0.003)**
Cross – Level Effect							
	Customer considers similar products			**0.9930**	**(0.209)**	**0.9704**	**(0.212)**
	Peer influence					**0.4524**	**(0.076)**
Bolded coefficients are different from null at the 95% confidence interval.							

that endogenous pure structural effects do not exist. Model 2 is similar to Model 1 and includes the pure structural effects and cross-level product association effects. By comparing Multidimensional Customer Product Network (MCPN) network modeling Models 2 and 1, one can test whether adding the pure structural effects and product association effect modifies some attribute-relation effects in explaining customer preferences. Model 3 includes all three types of ERGM effects. With the integration of the cross-level social influence effect, peer influences on preference decisions can be evaluated with other product attributes, customer demographics, and structural patterns within the same model.

Step 3: Interpretation of Results

The last step is to interpret and use the results from the network modelling step to understand how customer preference in considering two cars is affected by different configurations. The interpretation of Model 1 shows that the vehicle price has a significant negative sign, which implies that a lower price is preferred in consideration of luxury vehicles. The significant positive turbocharger and engine capacity indicate that the turbocharger's presence and the engine's increased size would increase the probability for a customer to consider a particular vehicle model. The statistically negative first-time buyers suggest that first-time buyers are unlikely to enter the luxury vehicle market even though first-time buyers in China purchase three out of four new cars. Fuel consumption has a significant positive coefficient, meaning that fuel economy is less important for customers who purchase a luxury vehicle. Interestingly, the decision of how many luxury vehicles to consider is less relevant to the household income, as seen by the insignificant income in the table. These findings about factors affecting customer preference can help car manufacturers introduce data-driven design interventions to increase their market share.

In Model 2, the addition of the pure structural effects and cross-level (customer considers similar products) effect considerably changes the interpretation of the underlying preference data. The significant positive product popularity indicates a dispersed degree distribution of product nodes. This implies that only a few vehicles were considered by most customers in the market. In contrast, the degree distribution is more uniform for customer nodes, as shown by the negative consideration range coefficient, because customers could only consider a limited number of vehicles (1–3) in the NCBS data. The “customer considers similar products” effect is an indicator of how likely is a customer to co-consider two vehicles that share similar design attributes. The “customer considers similar products” effect indicates how likely a customer is to co-consider two vehicles that share similar design attributes. The significant positive coefficient means most people, while judging a vehicle by its engineering attributes, would consider multiple vehicles with similar levels of performance and pricing. Concerning the attribute-relation effects, the change in price coefficient implies that price is not a decisive factor considered by luxury vehicle buyers. In contrast, the customer effects of first-time buyers and income level are more obvious. This is partly because thesurvey design controlled the number of decisions (degree of customer nodes), which limited it to a maximum of three cars. The coefficients of Model 3 are mainly consistent with those in Model 2. The significantly positive peer influence indicates that a customer is likely to be influenced by their peer. The authors in (Wang et al. 2016a) also report many interesting findings about the preference modelling in a multidimensional network context by comparing the above three models. This study shows how customer preferences for products can be modelled using statistical methods. By interpreting the coefficients of the ERGMs, product manufacturers can create data-driven interventions, where the changes can improve a product's market competitiveness. While the above networks focused only on the preference of customers while considering what cars to buy, next we discuss another case study, which discusses a different network-based approach to model the choice and consideration together in a network setting.

Case Study 2: Using MCPN for Modelling the Sedan Vehicle Choice in China

The previous study focused on a network approach to study which cars are considered by customers. In this study, we take an example of another method to model the problem, which helps in comparing how the customer preference differs between what products they consider buying and what they finally purchase. Specifically, this case study focused on sedan-type cars in the Chinese auto market. We adopt the same three-step structure to present the approach, i.e., (1) network construction, (2) network modelling, and (3) interpretation of results.

Step 1: Network Construction Based on Survey Data

The authors in (Fu et al. 2018) created two different networks as shown in Fig. 6 using the customer survey data which we discussed in the previous case study. In the first study, they created a bipartite network of cars and customers, where an edge between a customer and a car exists if the car was in the consideration set of the customer. In the second network, they create another bipartite network of cars and

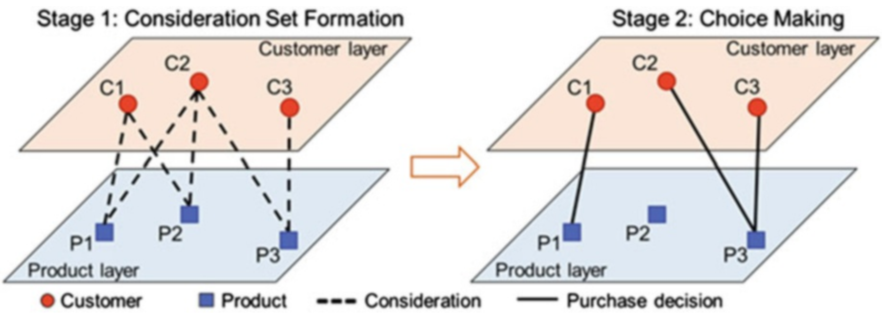


Fig. 6 Bipartite network for two-stage consider-then-choose modelling. The two-stage choice model assumes that each customer considers a subset of products first and then makes the final decisions. Researchers have access to both the consideration set and the final choice data

customers, where an edge exists between customers and the cars they bought. Unlike the first case study, they do not create edges between any two car models or any two customers.

Step 2: Network Modelling

Exponential random graph models (ERGMs) are used to capture the bipartite networks. The key variables included in ERGM were car attributes (like price, power, fuel economy, import, turbo, and brand origin to capture the economic, engineering, and branding effects on vehicle consideration and purchase), a few customer attributes (like whether a customer comes from a Tier 1 city or not), and network attributes (like geometrically weighted degree distribution). To compare their result with a baseline, the authors also trained a logistic model for purchase decisions as shown in the third column of Table 4 (without considering the network effect, i.e., the market distribution) with the ERGM applied to customer choice, conditioned on knowing their consideration.

The results show that the signs of the coefficients of fuel economy and brand origin (Europe) in the logit model are opposite to those in the exponential random graph model (ERGM). Results for the network model, with choice conditioned on consideration, indicate that given their consideration sets (two or three cars), customers are more likely to purchase cars that are cheaper ($\beta = -0.58$, $p < 0.001$), less

Table 4 Results of the logistic regression and bipartite ERGMs. *** represent significant values with $p < 0.0001$

		Logistic	Network model for consideration	Network model for choice
Car attributes	**Price**	−1.59**	−1.52***	−0.58***
	Fuel economy	−0.06	−1.21***	0.38
	Power	1.66***	1.55***	0.58*
	Turbo	−0.12	−0.24***	−0.14
	Import	0.82***	−2.29***	2.55***
	Brand origin (US)	−0.11	2.26***	−0.68***
	Brand origin (Europe)	0.91***	2.88***	−0.14
	Brand origin (Japan)	0.34***	1.15***	−0.17
	Brand origin (Korea)	−0.18	1.57***	−0.84***
Customer attributes	**Tier 1 × turbo**	0.07	0.32***	−0.08
	Tier 1 × fuel economy	0.15	−0.18	−0.002
Network effects	**Market distribution**	–	−2.25***	−15.36***
	Edges	00	−6.57***	0.02
Constant	**Constant**	−1.24***	–	–

fuel-efficient ($\beta = 0.38$, $p < 0.1$), more powerful ($\beta = 0.58$, $p < 0.05$), and imported ($\beta = 2.55$, $p < 0.001$). In terms of car brands, if a domestic brand is within consideration, customers on average are less likely to purchase the brands from the USA ($\beta = -0.68$, $p < 0.001$), Japan ($\beta = -0.17$, $p < 0.1$), or Korea ($\beta = -0.84$, $p < 0.001$). In terms of odds ratios, the probability of purchasing a car with a Chinese brand is 1.97 times the probability of purchasing the US brand car models and 2.32 times the probability of purchasing a Korean brand car model. Further, if a non-turbo car is being considered, on average customers from Tier 1 cities are less likely to purchase car models with turbo ($\beta = -0.08$, $p > 0.1$) than customers from non-Tier 1 cities. The negative coefficients for market distributions indicate that certain car models are more popular in China's sedan market.

Step 3: Interpretation of Results

A major contribution of this approach is the development of a two-stage network modelling approach to examine customers' consideration and purchase decisions, respectively. The Stage 1 model incorporates the interdependencies among vehicles and customers' preferences and predicts a customer's consideration set; the Stage 2 model characterises the purchase decision among the vehicles that the customer has considered. This study highlights six variables that significantly influence customers' consideration and purchase decisions: **price**, **import**, **fuel economy**, **brand origin**, **power**, and **turbo**. The two-stage models suggest that the factors that influence customers' consideration decisions are different from those influencing customers' purchase decisions. The results indicate that while the price is an influential factor in the first stage of forming a consideration set, it is slightly less prominent in the second (choice-making) stage since the consideration set is already filtered by price concern. Customers' preferences on some attributes are opposite in the two stages. The coefficients of fuel economy, brand origin, and turbo in Stage 1 and Stage 2 models show that fuel economy is preferred in determining the consideration set in Stage 1 (indicated by the negative coefficient − 1.21); but once the customers have identified a few alternatives, fuel economy is no longer a deciding factor and customers purchase the car model with less fuel efficiency (indicated by the positive coefficient 0.38) as compared to other alternatives in the consideration set. Similarly, for Stage 1, customers are more likely to consider domestically produced, non-turbocharged car models with foreign brands. However, after the consideration set is formed in Stage 1, customers tend to purchase the imported car models and those with Chinese brands. Therefore, although the Stage 1 consideration-only model helps gain insights into the processes by which customers form a consideration set, it does not capture customers' preferences in making the final choice.

The two-stage modelling approach offers rich insights into the key factors that would influence customers' consideration and choice decisions. These factors can be leveraged by different car manufacturers to introduce new interventions. Based on the knowledge gained from the consideration stage, in which customers have already picked the alternatives in a similar price range, people may still deliberate on the price and prefer to purchase the less expensive cars in the next stage. Besides, although customers try to consider cars that are more powerful in Stage 1, power becomes less important in Stage 2, potentially due to the consideration of price. Therefore, pricing strategies must be considered along with the design of vehicles to achieve the desired market share. Second, our findings suggest that car manufacturers might want to make the fuel efficiency of their car models attractive because it significantly influences customers' consideration decisions. Third, the results suggest that car manufacturers consider contextual factors, specifically city tiers, to account for the heterogeneity among customers, such as city tiers. For example, in more developed cities, such as the Tier 1 cities of China (e.g., Beijing, Shanghai, and Guangzhou), car manufacturers should emphasise the turbo feature of their products to attract more customers. Finally, manufacturers of foreign brands must consider strategies to address the challenge that their brands are more favoured in the consideration stage than in the purchase stage. Beyond vehicle design, the two-stage models are also relevant in the marketing and design of other types of products, such as small appliances, cell phones, computers, etc. Overall, this case study shows how survey data can be used to construct complex networks which simultaneously represent relationships between people and products, which can then be analysed to systematically study customer preferences in a complex system.

In this section, we began by introducing a network analysis method to study customer preferences and discussed how it offers more flexibility in modelling customer preference. Next, we showed examples of how statistical models can be used to model and interpret different types of customer preferences. These models provided key insights into various factors considered by customers in buying or considering buying a car. While the examples shown were specific to car customers, the network method can be used to study customer preferences and multi-stakeholder relations in many domains.

Conclusion and Outlook

In this chapter, we provided an overview of the data-driven approaches for multi-stakeholder decisions in engineering systems design and then use market as an example of an engineering system to demonstrate how an enterprise-driven decision-based design (DBD) approach can support rigorous engineering design decisions with multiple stakeholders. As modelling customer preference is an essential element of enterprise-driven design, the key focus of this chapter is on customer preference model. Particularly, we presented an approach to modelling heterogeneous customer preferences and choice behaviours based on the theory of complex networks and social science. With two case studies, the general steps of using networks as a methodological framework in customer preference modelling are introduced, and the advantages of the network-based approaches in visualising and modelling the complex interdependencies among different entities in a design ecosystem are demonstrated. The authors acknowledge there exist several challenges in this line of work. First, the current statistical modelling framework based on ERGM is limited to small-scale networks ranging from hundreds to thousands of nodes. The computational issues, particularly the convergence issue reported by domain experts of ERGM literature [ref], are significant barriers to scale up the application to more engineering systems where millions of nodes and links may be present. Second, there is a growing recognition that big data will become a key basis for supporting product improvement, product redesign, and product innovation. In the digital prosperity era, customers can now access abundant product data and reviews. This trend demands researchers to develop new techniques to integrate, analyse, visualise, and consume the growing torrent of big data. Aggregation of large-scale data from multiple sources presents unique challenges of identifying trustworthy sources. Third, the missing data issue has been a non-trivial problem in many previous studies. For example, the missing of rating data in a customer survey, the missing data of customer considerations, and the missing data of customers' social relations all pose challenges in developing a more comprehensive and robust network-based framework. Finally, the human factors and social aspects that existed in the complex customer-product system have been unavoidable sources for uncertainties, which causes many problems in prediction and often makes the validation of the proposed approach difficult.

Looking back at the advancement of research in customer preference modelling, it is clear that research in this field has expanded the scope of problem formulation from the traditional qualitative research to a more general quantitative framework in which not only individual customers' preferences can be modelled and elicited, but also can the interdependencies and interrelations among customers or between customers and product be explicitly modelled and predicted. Such a development greatly enhances the designers' capability in design automation, such as testing various design concepts and configurations before actual design takes place. In the future work, on the one hand, from the technical perspective, more recent developments in network science, such as the deep graph neural networks and network embedding techniques, provide us with new means of testing different assumptions underlying the customer decision-making process. On the other hand, from the methodological perspective, a framework that can incorporate other stakeholder's decisions is needed in support of engineering design from an ecosystem engineering point of view. For example, one possible avenue could be to extend the design formulation by incorporating the perceived value and preferences of stakeholders in the supply chain and distribution network. It remains a challenge of choosing the proper technique to model the market dynamics associated with multi-stakeholder dynamic decision-making. Overall, data-driven preference modelling methods can potentially transform the way decisions are made by multiple stakeholders by providing a systematic way to study interactions among multiple stakeholders in a complex design ecosystem.

Cross-References

► Architecting Engineering Systems: Designing Critical Interfaces
► Designing for Human Behaviour in a Systemic World
► Designing for Technical Behaviour

► Flexibility and Real Options in Engineering Systems Design
► Formulating Engineering Systems Requirements
► Human Behaviour, Roles, and Processes

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Formulating Engineering Systems Requirements

15

Markus Zimmermann and Olivier de Weck

Contents

M. Zimmermann (✉)
Laboratory for Product Development and Lightweight Design, TUM School of Engineering and Design, Technical University of Munich, Munich, Germany
e-mail: zimmermann@tum.de

O. de Weck
Engineering Systems Laboratory, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, USA
e-mail: deweck@mit.edu

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Abstract

Requirements are essential to coordinate purpose-driven activities distributed over several stakeholders. Requirements control the complex dynamics of socio-technical systems consisting of stakeholders and engineering artefacts and are, therefore, crucial for the success of socio-technical projects. Requirements management is challenging, in particular for complex engineering systems. This chapter discusses challenges (1) from a requirement receiver's perspective, focusing the indeterminacy of expectations; (2) from a requirement providers perspective, focusing on technical complexity; and (3) general challenges from an overall perspective. The chapter provides an overview of approaches to manage and treat requirements and links them to the core activities of requirements management: elicitation, analysis, triage, specification, as well as verification and validation. Typical forms of documentation and formulation rules are presented. Finally, we discuss the importance of quantitative analysis methods. Approaches based on simulation, isoperformance analysis, analytical target cascading, and solution space optimisation are briefly summarised.

Keywords

Design · Engineering systems · Methods · Requirements · Systems engineering

An Introduction to Engineering Systems Requirements

Purpose and Definition

While science aims at explaining the world as it is, engineering is about purposefully changing it by creating or modifying systems that would otherwise not exist. Goals that engineers pursue are therefore typically not expressed by descriptions of things that are already present in nature, but rather of those that are yet to be designed and made. These descriptions are initially formulated as requirements at various levels of detail. Requirements are descriptions of the desired behaviour (what it is supposed to do. . .), features (what it should have. . .), or properties (what measurement results are expected. . .) of a socio-technical system to be conceived, designed, implemented, and operated (Crawley et al. 2014). They are statements about the desired future state of the realised design, which can eventually be evaluated as true or false. They are often formulated using the verbs "shall" or "should". Whereby using "shall" the requirement must absolutely be satisfied, or otherwise the system design is not acceptable to the stakeholders. The use of "should" is softer and indicates a requirement that is desirable, but whose satisfaction is not condition sine qua non.

Requirements are used to **concretise stakeholder expectations**. In most procedure models of product development (e.g., phase-oriented models according to Pahl et al. (2007)), requirements are elaborated in order to communicate, explore, discuss, and agree on the direction of design work. They can be used for coordination of the development process within one organisation, but also in business-to-business

Fig. 1 DC-3 airplane. The requirements for the DC-3 included a payload of 21–32 passengers, a cruise speed of 200 knots and a range over 2,500 kilometres which was unprecedented at that time

relations. In that sense requirements are often included in legal and contractual documents and can be used to judge whether the delivered product or artefact is satisfactory (or not). Payment is only made once all "shall" requirements have been demonstrated or waivers to those requirements have been granted.

One of the most famous examples of how important requirements are is the design of the DC-3 aircraft in the mid-1930s. "The DC-3 resulted from a marathon telephone call from American Airlines CEO C. R. Smith to Donald Douglas, when Smith persuaded a reluctant Douglas to design a sleeper aircraft based on the DC-2" (Cunningham 2016) (Fig. 1).

Requirements also serve as a **management tool** at the interfaces between stakeholders with differing business interests or responsibilities. Stakeholders may comprise customers, eventual end-users, departments within an organisation, business partners such as contractors or suppliers, regulatory agencies, or any "party that may reap the consequences of the system-of-interest" (Haskins 2006).

Requirements frame a design problem and help narrow down the number of viable design candidates. Ideally, they are **solution-neutral**, i.e., they express only *what* is really relevant to the respective stakeholder, rather than *how* this target state can be reached (Pahl et al. 2007). In other words, they specify the result of a design process, rather than predetermine the design decisions that are necessary or sufficient to get there. It is important to leave sufficient design freedom to the recipient of the requirements. The recipient may have to satisfy other requirements or may identify solutions that should not be excluded by unnecessarily restrictive requirements. Thus, there is a fine balance between formulating too few requirements which leaves the stakeholder expectations fuzzy and undefined and defining too many requirements which limit design freedom.

It is often implied in the literature to formulate requirements at only one particular level of detail and all at once. However, practitioners formulate requirements **at various levels of detail and over multiple stages** of the development process. In the extreme, design is a nested process of breaking down requirements into new requirements organised in a vertical hierarchy, until the final design is specified with respect to all details; see, for example, Kim et al. (2003).

There is a significant difference between classical stage-gate and waterfall design processes in which ideally all top-level requirements are formulated upfront and the more **agile or spiral** development process where requirements are surfaced gradually as the design matures over time (Ulrich and Eppinger 2016).

In early design stages, **customer needs and business expectations** are expressed as unique and verifiable technical requirements levied on the product. They are ideally to be formulated such that they are – as an ensemble – sufficient (when satisfied) for meeting the stakeholder expectations. This is particularly challenging when expectations and needs are implicit, ambiguous, or volatile.

In later design stages, technical requirements on the product as a whole are often broken down into more detailed technical requirements often related to parts of the systems. The parts may be called subsystems, assemblies, modules, or components. Typically, parts of large systems like airplanes or road vehicles are designed in parallel to reduce development time. Parallel development often leads to circular dependencies and requires intense information exchange between the parallel strands of work. The complexity of a parallel development process can be reduced if requirements are formulated such that **they enable independent parallel design**. This can be realised, when requirements on the parts, first, can be verified by testing the parts only (i.e., while not connected to the rest of the system) and, second, are again formulated such that they are as a whole sufficient for satisfying the overarching requirements defined at a higher level in the system decomposition (Zimmermann et al. 2017).

Outsourcing the design and production of parts of the system to external suppliers is often managed while using requirements. They are usually cast into tender documents and define as a whole the sufficient condition for having satisfied a contractual agreement.

Requirements and Causality

In all three instances (addressing customer needs and business expectations, enabling independent parallel design, and outsourcing), requirements can be viewed as so-called INUS conditions, i.e., they are by themselves (i)nsufficient but a (n)-ecessary part of an (u)nnecessary but (s)ufficient condition (Mackie 1980). In other words, satisfying *all* requirements from a complete set, which necessarily includes all relevant requirements, is sufficient for satisfying a superior requirement or design goal. Satisfying only single requirements out of this set may not be sufficient. At the same time, they are not necessary, i.e., satisfying them is not the only possible way to satisfy the superior requirements. INUS conditions are a model for the link between cause and effect. In this sense, satisfying the requirements from the complete set can be thought of as the cause for the effect that a superior requirement or expectation is satisfied. This has two important consequences:

First, *satisfying only one or some requirements is in general not sufficient for satisfying a superior requirement*. In parallel development processes, designers may be aware only of those requirements that relate to their own technical responsibility. Unjustified single-factor thinking may lead them to assume that satisfying these local requirements will be sufficient for the entire system to work. This limitation in thinking is related to the human tendency to assume that systems are linear, where system outputs are weighted averages of lower-level design decisions. Most real systems, however, are not linear, and their behaviour is governed by non-linear and emergent responses that are not easily decomposable.

Second, *requirements are not unique*. Satisfying a particular set of requirements may ensure that a superior requirement is satisfied. However, this is in general also true for a different set of requirements. In other words, requirements are not necessary (conditions) for satisfying a superior requirement. Monocausal thinking may lead to fixation on pursuing a solution for one set of requirements, while a different set of requirements may permit a better solution.

Types of Requirements

Requirements are typically categorised by context, content, or degree of rigidity. As there is no universally accepted taxonomy of requirements, this section only reviews the most relevant and accepted types of requirements. A requirement may be of one or several types discussed here.

A typical distinction of requirements is made between **customer requirements** and **technical requirements** (VDI 2221 2019). While the first type attempts to capture often implicitly expressed needs and expectations of non-experts, the second type tends to be formal and concrete and is expressed by technical experts. An important engineering activity is the translation of customer requirements into technical requirements.

Functional requirements represent one of the most common categories (Haskins 2006; NASA 2007; IEEE 1998; Pohl and Rupp 2021). Functional requirements specify what the system shall do in a non-quantitative sense, e.g., “The thrust vector controller shall provide vehicle control about the pitch and yaw axes.” One of the ways to do this is to define the actions or activities that a system shall carry out in the form of a concept of operations (CONOPS); see next section.

Non-functional requirements are, by contrast, related to attributes, e.g., quality and performance measures (Pohl and Rupp 2021). For a review on differing definitions of non-functional requirements and an attempt to reconcile them, see Glinz (2007). A narrower definition of non-functional requirements is related to those qualities that go beyond the observable actions of a system in the short term, but include its behaviour over the full life cycle. Life cycle properties are also referred to as the *ilities* as many of them end in the suffix “-ility” such as usability. This last example is important for systems that interact directly with humans (see ISO 13407: 1999, Ergonomics – Ergonomics of human-system interaction – Human-centred design process for interactive systems). One of the challenges with life cycle properties is that they can form polysemy and synonymy relationships and are often not easy to verify or validate (de Weck et al. 2012). More recently sustainability requirements (low or no emissions, ease of recycling, etc.) are becoming more important in system design.

Performance requirements define a quantitative level of performance (NASA 2007), e.g., “The vehicle shall accelerate from 0–100 km/h within 5 seconds”. These requirements are often tied to particular operating modes of the system or product and can be linked to the parent functional requirement to which they apply. An important consideration is that the way in which performance requirements are verified should be known at the time they are specified. There may be multiple non-unique designs that satisfy the same set of performance requirements (iso-performance); see de Weck and Jones (2006). Performance requirements are not to be confused with **specifications** which rather refer to specific detailed descriptions of a product to be built (VDI 2519 2001).

While the previously mentioned requirements are applied to the resulting system design or product, i.e., the outcome of the design effort, **process requirements** are imposed on the process itself. An example of this is the imposition – inside the requirements – of the use of certain ISO, MIL, DIN, or IEEE standards. For example, when it comes to defining performance measures and metrics, one may be asked to follow ISO/IEC 15939 that provides a process to identify, define, and use appropriate measures or ISO/IEC 9126, which is a series of standards provided to define relevant quality measures. Most modern cyber-physical systems contain both hardware and software. The definition of software requirements often follows IEEE standards, but may also follow a more ad hoc agile process, particularly for non-safety critical software that is not embedded in devices such as medical devices that are subject to certification and approval by regulatory authorities. Newer systems in the life sciences contain significant biological elements beyond innate hardware and software. How to specify requirements for biological systems, in addition to the better understood hardware and software requirements, is new territory for requirements engineering. An area to watch closely is the emergence of requirements in synthetic biology (Purnick and Weiss 2009).

Constraints are requirements of particular rigidity, i.e., they cannot be traded off by tightening another requirement while still satisfying a superior requirement. They may be applied to both, processes or system designs and products. For example, “The weight of the vehicle shall not exceed 1.5 tons.” These constraints often apply to the use of resources in the design of physical systems such as size, weight, and power (SWaP). Often, constraints are derived from government regulations or admission criteria, like the CE marking.

Typically, requirements are not written in isolation, but as part of a larger program or project. Figure 2 shows how both programmatic requirements (typically related to cost and schedule) and technical requirements are derived from parent **program and project requirements**. As an example, the following level 0 policy requirement, driven by science and society, which eventually is broken down into technical requirements, was formulated for the Roman Space Telescope by NASA (NASA 2021): “This observatory shall help unravel the mysteries of dark matter and dark energy in our universe to help determine and refine its rate of expansion and ultimate fate”.

Requirements Management

Process

A nominal requirements management process is depicted in Fig. 3. At the start of a new project or undertaking, the first step should be to perform a stakeholder analysis. In commercial firms this often means dividing the market into different segments of customers which may have different needs and preferences. From the stakeholder

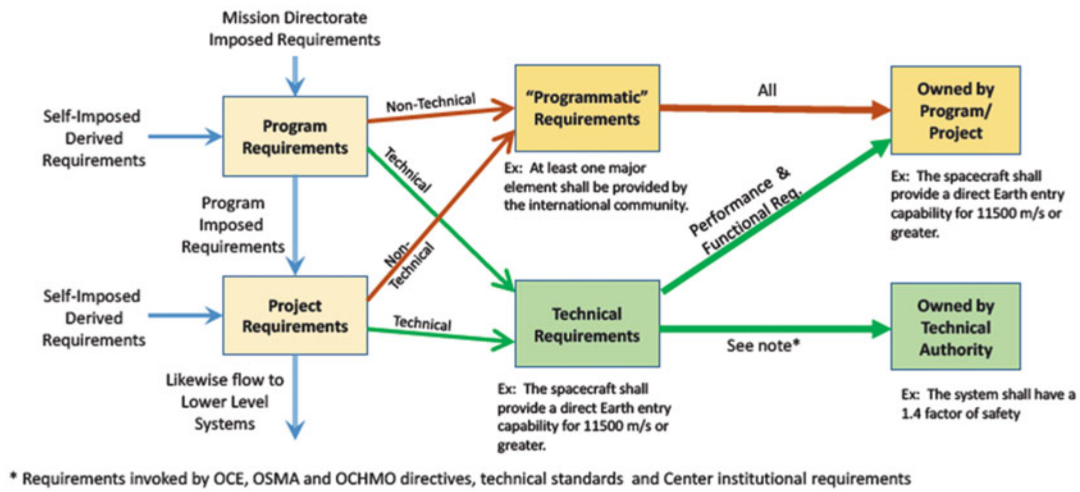

Fig. 2 Example of flow, type, and ownership of requirements (NASA 2007)

analysis, one can extract high-level requirements which address the functions, levels of performance, and constraints the system must satisfy. Another important stakeholder – besides customers – is regulatory or certification agencies that impose standards, laws, and regulations on the system. Examples of highly regulated industries are the medical device industry, the nuclear industry, agriculture, and food production, as well as the automotive and commercial aviation industries. These have in common that human health and welfare are at the centre of their considerations.

Setting and deriving requirements is often more challenging than it first appears. Missing requirements are often discovered late and can cause expensive rework in projects. Redundant or poorly written requirements can cause confusion and avoidable errors during the design process. Overly stringent requirements may lead to great effort that is not absolutely necessary to achieve success. As shown in Fig. 3, requirements should be set using both clear metrics and target ranges or values. Methods to compute quantitative requirements are described in section "Quantitative Analysis Techniques". Once set, functional deployment can occur, and lower-level requirements and concept development lead to an implemented design solution.

In system verification we close the inner loop in Fig. 3 and check the implemented design against the requirements set, as written. This can occur with the help of models, testing of physical prototypes or by inspection. The essential question here is: "Are the requirements attainable?", "Does the system as designed or as built meet the requirements as written?". This process is known as verification. Verification occurs from the bottom up, meaning that one first checks the requirements compliance of lower-level components and subsystems, before proceeding to higher levels. It may not be a one-shot process, but an iterative one. The verification

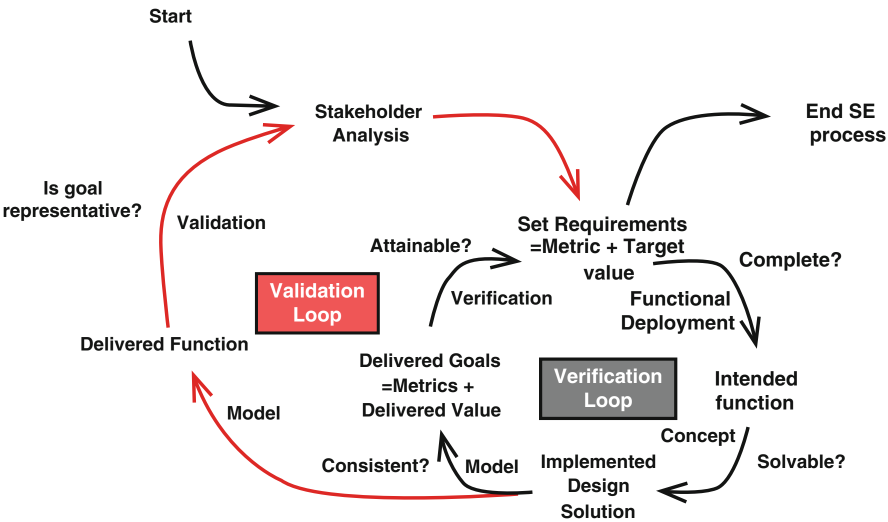

Fig. 3 Nominal requirements management process

loop may have to be traversed many times in order to establish clearly which requirements are satisfied and which ones are not. In many projects it is necessary to adjust requirements to make them feasible, to revise the design, or to request a formal waiver from stakeholders when requirements cannot be satisfied as stated. System verification is often performed in a laboratory setting, under highly controlled conditions to minimise the effect of both internal and external disturbances.

Figure 3 also illustrates the outer loop where the delivered function of a system is demonstrated to the original stakeholders in order to obtain their concurrence that the system delivers the function that was intended and that the system delivers value. This is known as the validation loop. This is the moment of truth for many systems, since it reveals not only if the implemented design solution performs according to the requirements but also if the goals that were set for the system were representative of the original stakeholder intent. It is possible, and unfortunately not uncommon, that a system passes verification, but fails validation. Validation is typically not performed in a highly constrained laboratory setting, but in the real world under actual or simulated operations. This introduces many noise factors such as user or operator errors, challenging meteorological conditions, and unanticipated interactions with other systems.

Updating and changing requirements is a continual process (VDI 2221 2019): "Knowledge acquired during the design process can mean that existing requirements have to be changed and new requirements added. In accordance with the central importance of requirements, changes or additions to the requirements have to be made and documented continuously and consistently as well as being open at all times towards change requests made by product planning or the customer. The definition and use of the requirements does not end with the release of the design documentation, but continues when the product is realised."

Activities

Requirements management involves typical activities:

- **Elicitation**, i.e., "learning, uncovering, extracting, surfacing, or discovering needs of customers, users, and other potential stakeholders" (Hickey et al. 2004).
- **Analysis**, i.e., "analysing the information elicited from stakeholders to generate a list of candidate requirements, often by creating and analysing models of requirements, with the goals of increasing understanding and searching for incompleteness and inconsistency" (Hickey et al. 2004). When designing complex systems, this activity also involves **breaking down requirements**, i.e., identifying lower-level requirements that are sufficient for satisfying superior requirements. This is an important contribution to decomposing large design problems into smaller and more manageable pieces.
- **Triage**, i.e., "determining which subset of the requirements ascertained by elicitation and analysis is appropriate to be addressed in specific releases of a system" (Hickey et al. 2004).

- **Specification**, i.e., “documenting the desired external behavior of a system” (Hickey et al. 2004).
- **Verification and validation** to ensure that “the product was built right” and “the right product was built”, respectively (NASA 2007); see also the previous section.

In long-lived programs that are around for many years (e.g., defence systems, infrastructure systems like the electrical grid) and that evolve by infusing new technologies over time, it is crucial to repeat these activities periodically to provide updates of requirements.

An overview over the methods that support these activities is provided in section “Overview over Approaches and Methods.”

The Socio-Technical Nature of Requirements Management

Requirements are typically formulated at the interface between stakeholders which have individual interests and pursue individual goals. This yields naturally different perspectives for each requirement, the provider’s, and the receiver’s perspective. The provider expresses an expectation, a desire, or a need through a requirement. The receiver is requested to commit to satisfy the requirement by making it a goal for their future activities. Both perspectives are associated with particular and different challenges that will be discussed in detail in the following sections. This section provides a formal framework to explain the two perspectives in detail and, thus, identify how stakeholder activities and the technical aspects are related.

Figure 4 shows a simple model, abstracted from Zimmermann et al. (2017), of stakeholders and dependencies between description elements z_i, y_j, $x_{k,}$ … (where i, j, k denote indices of unspecified range) of any object that shall be subject to requirements. The term *object* is not reduced to material things but may be any socio-technical construct, such as a process or a combined system of product and user. These description elements represent aspects of the system that are important to stakeholders. They include characteristics, properties, attributes, qualities, behaviour descriptions, sensations, and any kind of metric that can be attached to the object or system under consideration. For physical components, description elements can be, e.g., measures of size, material properties, and interface properties, amongst others. For software components they can be, e.g., the number and type of inputs and outputs as well as the response time of computations. For processes, the descriptions elements can be, e.g., duration or communication frequency. For a concrete example from vehicle design, see section “Target Cascading and Solution Space Optimisation.”

Thin arrows between description elements in Fig. 4 indicate the influence of one description element on another. If, for example, the object under consideration is a mechanical structure, its material properties x_k will influence its strength represented by y_j. Or, if the object under consideration is a development process, the frequency of meetings of design teams x_k will influence the exchange rate of information y_j.

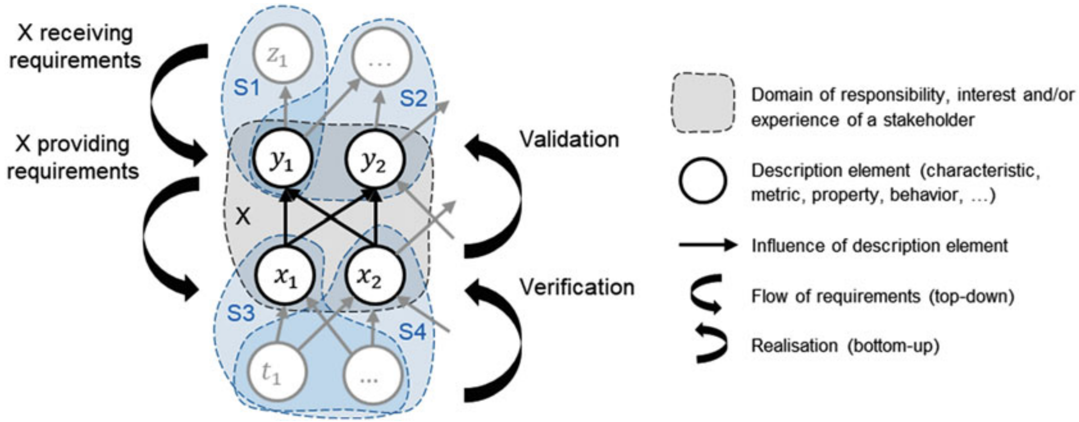

Fig. 4 Receiving and providing requirements from stakeholder X's perspective. Other stakeholders are denoted by S1, S2, S3, S4

Detailed description elements are located on the bottom of the object under consideration. By combining them and letting them interact, new description elements emerge representing, e.g., properties of an ensemble of combined components or subsystems. Consequently, description elements for the entire object or system, such as performance measures or ilities (de Weck et al. 2012), are at the top level.

Providers of requirements have expectations, desires, and needs (for brevity we will further address all three only as expectations) that they cast into requirements *on* description elements. Requirements are not to be confused with the description of the elements themselves. While description elements describe an object as it *is*, requirements express an expectation of what they *shall be* (or, more precisely, what values they shall assume or how they shall be instantiated). For example, a requirement on a mechanical system may be that its strength y_j shall exceed the threshold value y_c. A requirement on a development process may be that the meeting frequency between teams y_j shall exceed (or not) the threshold value y_c.

Description elements are assigned to stakeholders to express that stakeholders accept responsibility or pursue interests related to them. Figure 4 shows several stakeholders with shared interfaces indicated by shared description elements. Stakeholder S1 pursues a goal related to description element z_1 which is influenced by y_1. A change of y_1 may cause a change of z_1, possibly not desired by S1. If stakeholder X can control y_1, they can act as a receiver of a requirement on y_1 provided by S1. Figure 4 shows that stakeholder X has only indirect control over y_1, because it is again influenced by x_1 and x_2 which are in turn controlled by stakeholders S3 and S4, respectively. This is a typical scenario, e.g., representing suppliers contracting sub-suppliers. Therefore, stakeholder X acts first as a receiver of requirements at the interfaces with S1 and S2 and then provides requirements at the interfaces with S3 and S4. The interfaces S1-S2-X and X-S3-S4 do not differ conceptually. Therefore, breaking down requirements can be seen as a nested process that is self-similar.

The direction of influence between technical description elements is opposite of the direction in which requirements propagate. Using this definition of hierarchy, stakeholders providing requirements first will be called *superior* stakeholders, i.e., S1 and S2 are superior to X.

Receiving requirements is about understanding a superior stakeholder's expectation. S1 ideally provides unambiguous requirements on y_j that are such that, when satisfied, S1's expectations related to z_1 will be satisfied. In other words, requirements on y_1 should be sufficient to satisfy requirements on z_1. This is often not the case; therefore stakeholder X may be involved in or even drive the process of identifying them. Due to limited information, stakeholder X may encounter significant challenges to elicit meaningful requirements on y_j. This *indeterminacy of expectations* will be explained in more detail in the following section.

Providing requirements is about identifying conditions on x_k which are sufficient to satisfy the requirements related to y_j and communicating them to another receiver of requirements. The associated challenges are mostly driven by *technical complexity*, i.e., by the degree to which the technology and resources to be employed are unknown or uncertain, the lack of existing experience and knowledge in relation to the task, the number of components or states involved, and the degree of interaction between components and variants of the product or process to be developed. Managing technical complexity will be discussed in more detail in section "Managing Technical Complexity: The Provider's Perspective."

Managing Indeterminacy of Expectations: The Receiver's Perspective

This section discusses challenges that are typical of requirements management from the perspective of the receiver of requirements and contribute to the *indeterminacy of expectations*. Approaches to avoid their causes or mitigate their effects are provided.

Ambiguity. Expectations may be ambiguous for several reasons. One important source of ambiguity and misinterpretation is human natural language. Also, criteria for satisfying expectations may be highly subjective and therefore difficult to grasp for the receiver. This is the case, when they are based on sensations that are difficult to describe. For example, the haptic steering feel of a road vehicle is difficult to express by technical metrics (Nybacka et al. 2014) and consequently difficult to subject to formal requirements for the vehicle designer. In Fig. 4, the haptic sensation of the steering feel would be y_1 that influences the subject impression z_1 of the superior stakeholder in terms of how sporty the vehicle feels. Finally, expectations may be vague initially and only concretise with the experience of solution candidates. Sutcliffe et al. (2013) called this the "I will know what I want when I see it" problem.

Approaches to reduce ambiguity are, for example, Design Thinking to empathise with the stakeholder or benchmarking to identify analogues (Brown 2008). There is also a recent desire to formalise requirements specifications in formal models to reduce ambiguity. Such models exist in digital form and increasingly conform to systems modelling languages such as OPM (Dori 2011), SysML (Matthew 2006), or Modelica (Fritzson and Engelson 1998). Approaches to minimise the consequences of ambiguity are agile approaches in general and prototyping (Matthew et al. 1992) in particular (including rapid prototyping): By producing a functional design as quickly as possible and showing it to stakeholders and gathering feedback rapidly, it is possible to close a feedback loop and reduce ambiguity. In practice, it is often the case that after about three iterations, the ambiguity is substantially reduced. However, this approach to ambiguity reduction has mainly been applied to software only and is just starting to emerge for hardware-intensive development projects.

Volatility. Expectations and requirements may change due to conflict between many stakeholders (Peña and Valerdi 2015) or because implicit or unknown expectations become explicit. Requirements creep describes a phenomenon where expectations slowly grow (NASA 2007), often without sufficient addition of resources such as schedule and budget to meet the expanded set of requirements. Figure 5 shows the larger impact of requirements volatility on development projects and the associated systems engineering effort. In some cases, the number of system requirements can decrease; however such descoping is rare in practice.

Volatility may be reduced by removing as much ambiguity as possible at the beginning of a project. Agile approaches and their methods (Belling 2020),

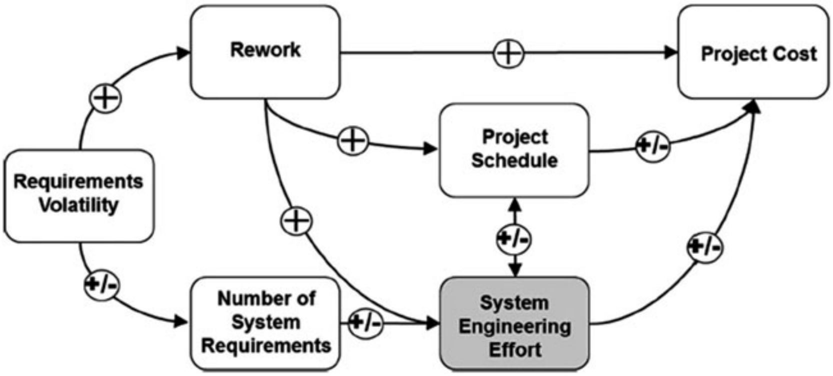

Fig. 5 Wider impact of requirements volatility on the systems engineering effort (NASA 2007)

including prototyping (Matthew et al. 1992), help to alleviate the consequences of volatility.

Completeness (I). In the context of receiving requirements, this is the quality of being sufficient to satisfy the expressed and possibly not formulated expectations of the superior stakeholders. Completeness is a challenge, because in some settings, it is difficult to make sure that everything relevant was considered. This may include aspects that are not known to the superior stakeholders or are even intentionally hidden, like secret values or political agendas. "Knowing what you do not know is one of the biggest challenges faced by analysts" (Hickey et al. 2004).

Incomplete requirements may result in not meeting a stakeholder's expectation. However, the model of *co-evolution of problem and solution space* offers an interesting alternative view of incompleteness: it may serve as a trigger for creativity and a constructive adaption of the scope of the design problem and its corresponding solution (Dorst and Cross 2001). Thus, incompleteness of requirements can be regarded as a means to avoid *requirements fixation* (Mohanani et al. 2014).

Approaches to increase completeness for the receiver of requirements are, for example, *storytelling* (Lloyd 2000), *customer journey* (Richardson 2010), *benchmarking* (Camp 2007), etc. The consequences of incomplete requirements can be alleviated by agile approaches and prototyping: see above.

Example: IBM Federal Systems – Air Traffic Control (G2B)

In the development of the FAA's Advanced Automation System (AAS) (Cone 2002), many of the abovementioned issues and challenges were manifested. A new software system was developed to automatically manage air traffic by IBM Federal Systems. A total of $2.6 Billion was spent on a system that ultimately failed validation. One of the reasons for this, besides the complexity of the system requirements, was that the technology was immature and that a successful AAS would have potentially eliminated many high-paying jobs for human air traffic controllers. ◄

Managing Technical Complexity: The Provider's Perspective

This section discusses challenges that are typical of requirements management from the perspective of the provider of requirements and contribute to *technical complexity*. Approaches to avoid their causes or mitigate their effects are provided.

Completeness (II). Requirements provided by a stakeholder shall be sufficient to satisfy their own expectations or requirements. In Fig. 4 this translates to requirements on x_i being sufficient for satisfying requirements on y_j. Formally proving the completeness of a requirements set is difficult in practice, particularly for heterogeneous cyber-physical systems containing many hardware and software elements. In the field of formal software verification in computer science, however, some progress has been made on proving completeness for some problems such as Air Traffic Control (ATC) software (Odoni et al. 2015). Quantitative requirements formulated as so-called solution spaces (see section "Target Cascading and Solution Space Optimisation") are shown to be complete in a statistical sense using random sampling in the part of the design space that is enclosed by the requirements (Zimmermann et al. 2013). This is possible, however, only for systems that can be represented by appropriate analytical or numerical simulation models.

In industrial practice, requirements are often not complete. One reason for this is technical complexity, typically related to unknown or non-linear interactions between components. Another reason is the need for feasible requirements (see below), often resulting in relaxed requirements, that are not sufficient at the upper level. Finally, engineers are often not willing to put much effort into making them complete. Typical are "old and informal business relationships" (Weber and Weisbrod 2003) between stakeholders. Informal and trustful relationships can alleviate the consequences of incomplete requirements because iterations and bug fixes may be possible. On the downside, however, they may lead to dependence on the partners.

Incomplete requirements may become toxic when combined with outsourcing and strong cost minimisation efforts. In large companies, responsibility for performance and functionality is often separated from the responsibility for cost. Engineers, responsible for the first, provide technical requirements while purchasing agents, relying on their completeness, spur competition between several suppliers to make them reduce cost as much as possible, and finally opt for the inferior offer with the lowest price. If requirements are nevertheless satisfied, payment must be made, even when superior requirements are violated due to inferior quality.

In systems engineering, incompleteness is taken into account by the V-model (Haskins 2006), which includes iterations after unsuccessful verifications and validations. Approaches to support engineers in identifying complete requirement sets comprise modelling and simulation (de Weck and Jones 2006) and methods like FMEA analysis (Stamatis 2003). Agile approaches (Belling 2020) avoid this challenge by not even trying it. Instead, they incrementally add top-level requirements and iterate.

Example

Retractable landing gear of a helicopter (Micouin et al. 2018). In this case the requirements for a helicopter landing gear controller were elaborated using the Property Model Methodology (PMM). This approach helped discover missing requirements from a logical perspective, for example, what should happen if the pilot reverses the landing gear retraction mechanism before landing gear retraction is completed (a process that takes several seconds). Without a specific requirement, the situation remains ambiguous and could be interpreted in different ways:

- The pilot input is ignored until the landing gear retraction is completed.
- The landing gear retraction is suspended, and the landing gear remains frozen in its current position.
- The landing gear retraction is reversed immediately by the system, and the landing gear is brought as soon as possible to the deployed state.

Especially with software-intensive systems, the number of possible states that a system can be in is in the hundreds, thousands, or even the millions. Without requirements analysis, models, and scalable tools, it is easy to forget key requirements that can result in future unsafe states or accidents. ◄

Feasibility. Good requirements are feasible. The provider shall formulate them such that the receiver can satisfy them within available means and with reasonable effort. It can be difficult for the provider to anticipate what the receiver is able to realise, as he or she requires knowledge about another stakeholder's domain of responsibility or experience; see Fig. 4. It becomes even worse when little is known about the underlying technology or resources. Feasibility may be increased by making requirements less restrictive to provide design freedom for the subordinate stakeholder. This, however, needs to be balanced with completeness to ensure that the requirements are still sufficient for satisfying superior requirements. Feasibility may be supported by relying on engineering expertise and reference designs. Solution space optimisation (Zimmermann et al. 2013) is a technique that maximises design freedom while maintaining sufficiency to satisfy superior requirements; see section "Quantitative Analysis Techniques."

Uncertainty addresses the challenge related to the lack of knowledge about the resulting system to be developed. This includes the risk of requirements not being satisfied, e.g., due to the lack of completeness or feasibility or reasons related to organisational aspects. It is relevant when requirements are formulated for separate components that interact. Whether a requirement on one component is sufficient to satisfy a superior requirement may depend on the *realised* performance, behaviour, etc., of all other components. However, these components do not yet exist, because they are still to be developed. Their performance, behaviour, etc. are uncertain and may deviate from their target for several reasons: They may be difficult to adjust, e.g., due to production-related variation, inherent material scatter, or degradation. In addition, the components may be subject to other requirements, possibly unknown to stakeholder X in Fig. 4, e.g., related to manufacturability or cost, or product variants using the same component. One strategy to account for uncertainty is to relax requirements in a controlled way to enclose possible deviations from a desired state. This again needs to be balanced with completeness.

Learning that requirements on some components cannot be satisfied may require readjusting other requirements, possibly triggering a long sequence of changes; see section "Process."

Approaches to treat uncertainty include uncertainty quantification and assessment methods including Monte Carlo simulations (Peherstorfer et al. 2018), solution space optimisation (Zimmermann et al. 2013), set-based design (Sobek et al. 1999), and FMEA (Stamatis 2003).

Integrability refers to the absence of conflicts between requirements. When many stakeholders pursue different goals and strive for optimality from their perspective, they may cause conflicts of technical and finally non-technical nature; see Fig. 6. Ideally, providers of requirements formulate them such that they can be satisfied by the receiver without violating other requirements (Zimmermann et al. 2017). This can be achieved by assuming other stakeholders' view and understanding their goals, limitations of resources, and constraints, requiring extra effort and intense communication. Formulating requirements as least restrictive as possible while still ensuring the achievement of goals is an effective alternative. This approach has a striking similarity to negotiation strategies (Fisher et al. 1999). Approaches to increase solution neutrality are discussed in the next paragraph.

Solution fixation. Designers tend to think and work with concrete designs or realised products. Therefore, it is typically difficult for them to formulate solution-neutral requirements rather than specifying concrete solutions. The focus on apparent solutions rather than solution-neutral requirements serving underlying needs prevents the integration of interests of several parties; see Fisher et al. (1999). Approaches to support solution neutrality are creativity techniques like mind mapping (Buzan and Buzan 1996), seeking solution spaces rather than specific solutions (Zimmermann et al. 2013), or set-based design (Sobek et al. 1999) and morphological charts (Pahl et al. 2007) that invite to think in alternatives.

Optimality. Decomposing requirements into requirements with design freedom for receiving stakeholders bears the risk of obtaining suboptimal results. Making requirements more restrictive to stay close to the optimum is in direct conflict with feasibility. Finding a good balance between the two is supported by model-based systems engineering, or MBSE (Madni and Sievers 2018), Isoperformance Analysis (de Weck and Jones 2006), and numerical optimisation (Papalambros and Wilde 2017).

General Challenges: The Overall Perspective

This section discusses challenges that are relevant to everybody involved in requirements management, including those that neither provide nor receive requirements

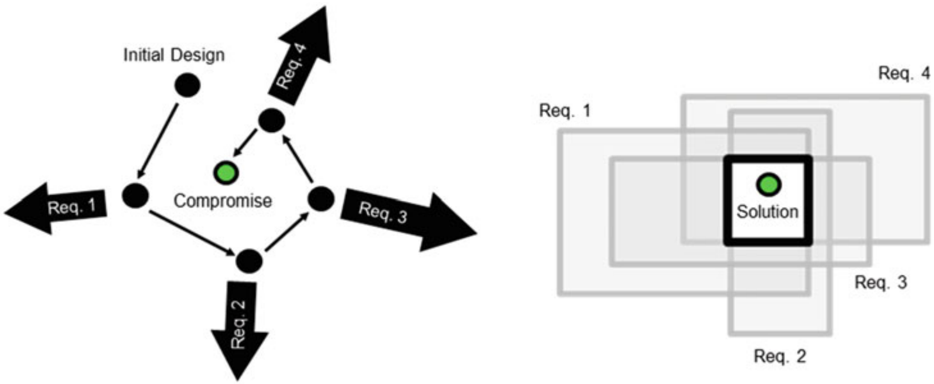

Fig. 6 Conflicting requirements (left) vs. integrable requirements (right)

themselves, like requirements managers, and proposes approaches to avoid their causes or mitigate their effects.

Requirements proliferation. In an attempt to provide complete sets of requirements for complex systems, engineers tend to add to existing ones. To make things worse, requirements are rarely removed (Weber and Weisbrod 2003) for two reasons: First, they have accumulated over years, and nobody understands the consequences of removing a requirement due to technical complexity. Second, the individual risk of removing a requirement and thus producing an incomplete set (with the risk of not meeting the individual superior requirements) outweighs the general advantage from one stakeholder's perspective. The result is overly extensive sets of requirements that may be unnecessarily restrictive causing development effort and preventing simple solutions. Large engineering projects often struggle with a very large number of requirements. For example, automotive electrical systems are subject to hundreds of pages of specifications and related documents (Weber and Weisbrod 2003). The recent development of the Airbus A350 long range aircraft was challenged with over 200′000 requirements across the whole program. Model-based management of requirements (Bernard 2015) and documentations tools, like relational databases such as DOORS (Hull et al. 2005), help to maintain the overview over large collections of requirements.

Traceability refers to the documented relationship between parent and child requirements. Each requirement, except for top-level or root requirements, should be traceable to at least one parent requirement. And each requirement, except for the lowest-level leaf requirements, should have at least one child requirement that ensures its ultimate implementation in the constituent parts of the system. Traceability can be in conflict with requirement proliferation, as "Traceability is a great feature – the real challenge, though, is to decide which traces to maintain" (Weber and Weisbrod 2003). Traceability can be checked using formal databases and data analytics and should, for example, prevent the existence of so-called orphan requirements that are not connected to any other requirements in the project or program.

Choosing a Design Approach

Phase-oriented, stage-gate, water-fall-type or linear procedure models (Pahl et al. 2007) are appropriate when, first, top-level requirements are static, unambiguous, and complete and, second, the level of technical complexity is comparatively low. The V-model of systems engineering (Haskins 2006) addresses increased technical complexity by incorporating iteration loops. It still relies on capturing a complete set of system-level requirements.

Agile approaches are particularly useful in development situations when, first, stakeholder expectations are indeterminate (volatile, ambiguous, or incomplete) due to many or implicit or conflicting stakeholder expectations, or, second, the level of technical complexity is high due to unknown technology, little experience, or many interacting components. Rather than attempting to incorporate all requirements from the beginning like phase-oriented linear development processes, agile approaches satisfy requirements one-by-one, focusing on the most relevant first. This increases the chance to successfully capture implicit requirements by early failure. Also, wrong paths are detected earlier and can be adjusted. Agile is not necessarily faster, however, customer satisfaction tends to be higher (Atzberter et al. 2019) (Fig. 7).

Overview over Approaches and Methods

A list of approaches to elicit, analyse, prioritise, specify, and verify requirements is shown in Table 1. Approaches include, ordered from general to specific, design philosophies, procedure models, methods/techniques, and tools. Each approach is assigned either to one dominant activity or all activities from section "Activities" and the addressed challenges explained in sections "Managing Indeterminacy of Expectations: The Receiver's Perspective", "Managing Technical Complexity: The Provider's Perspective", and "General Challenges: The Overall Perspective."

Quantitative analysis methods that are particularly relevant for engineering systems are discussed in more detail in section "Quantitative Analysis Techniques."

Documenting Requirements

Types of Documentation

A critical issue in the formulation of system requirements is how the requirements are captured and documented. This is generally done using a combination of human natural language (written and oral), graphical representations, mathematical expressions, as well as more recently formal models. This section describes the different types of requirements documentation we typically encounter (Fig. 8).

Story boards are cartoons that are easy to read and understand and that can form the seeds of functional requirements. The main advantage of story boards is that they do not require detailed technical domain knowledge. The downside of storyboards is that they may lead to incomplete or nonsensical requirements or cause "lock in" by preventing other use cases that are not on any story board from not being considered (Fig. 9).

A **customer journey** is a technique for following a typical customer or user throughout their day along with their hypothesised or actual thoughts, activities, and emotional states (happy, neutral, sad). By collecting such customer journeys deliberately for a significant number of individuals, patterns, and opportunities may emerge for new or improved products and services. These patterns may then be turned to requirements for system or product design (Fig. 10).

Eventually, requirements are most often written down in human natural language and collected in **requirement lists**. This is convenient but can also lead to confusion since human natural language has many non-unique ways of expressing the same or similar facts or statements. Figure 10 shows some of the best practices in

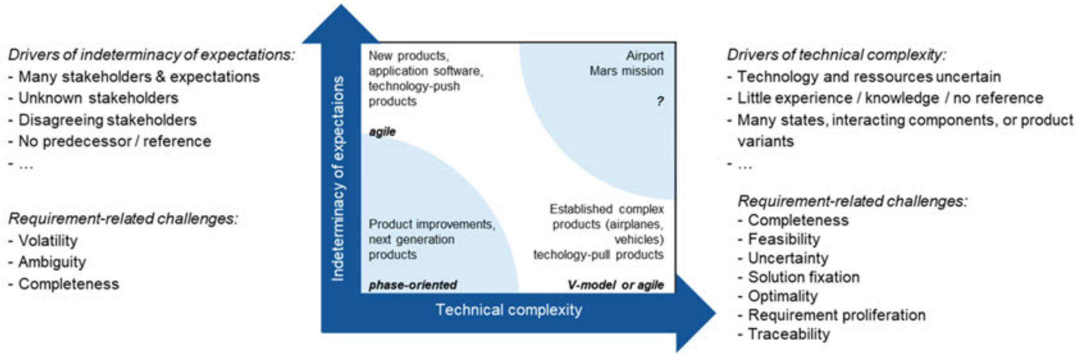

Fig. 7 Recommended design approach based on indeterminacy of requirements and technical complexity

Table 1 Sample of approaches to managing requirements

Name	Type	Involves activity	Volatility	Ambiguity	CompletenessI	CompletenessII	Feasibility	Integrability	Uncertainty	Solutionfixation	Optimality	Proliferation	Traceability	Description	Reference
Acceptance test	Method	Triage		X	X									Provides user/ customer feedback with a prototype	Martins Pacheco et al. (2020)
Agile hybrid models	Procedure model	All	X	X	X		X					X		Combination of plan-based and agile procedures. Examples: “AgileFall”, “ScrumBan”, LeanBan”, “FrAgile”, etc.	Belling (2020)
Agile philosophy	Philosophy	All	X	X	X		X					X		Philosophy of design where development goal is not captured as a whole but rather approached by formulating and realising increments	http://www.agilemanifesto.org
Agile stage-gate model	Procedure model	All	X	X	X		X					X		The integrated agile-stage-gate hybrid model – a typical 5-stage, 5-gate stage-gate idea-to-launch system, with agile built into each of the stages	Cooper and Sommer (2016)

ATC	Tool	Analysis				X	X	X			X			Analytical target cascading is a numerical hierarchical multi-level optimisation to break down requirements from the top to the detailed level	Kim et al. (2003)
Benchmarking	Method	Elicitation		X	X	X	X	X						Method to systematically assess the performance of competitors' products and identify for best practices	Camp (2007)
Business epic	Method	Elicitation		X	X									"An epic is a container for a significant solution development initiative that captures the more substantial investments that occur within a portfolio." hypothetical business goals, collection of user stories	Knaster and Leffingwell (2020)
Checklists	Tool	Elicitation			X	X								Lists of typical candidate properties that may have to be subjected to requirements (e.g., size or weight) for technical products	Ponn and Lindemann (2008)

(continued)

Table 1 (continued)

Name	Type	Involves activity	Volatility	Ambiguity	CompletenessI	CompletenessII	Feasibility	Integrability	Uncertainty	Solutionfixation	Optimality	Proliferation	Traceability	Description	Reference
Customer journey	Method	Elicitation		X	X									"Technique to capture the interaction of your customers with your company, product, online experience, retail experience, service, etc."	Richardson (2010)
Design thinking	Procedure model	Elicitation		X	X	X								Design thinking is an iterative approach to empathise with the user/customer and develop solution concepts that are evaluated by the user/customer	Brown (2008)
Documentation tools	Tool	Specification											X	Database applications that support requirements documentation and management (e.g., DOORS)	Hull et al. (2005)

FMEA	Method	Verification				X			X					The failure modes and effects analysis is a scheme to support identification and assessment of possible failures and associated risks	Stamatis (2003)
Interviews	Method	Elicitation		X	X									For information extraction from stakeholders. Ranging from unstructured (for exploration) to structured (for focus and completeness)	Zowghi and Coulin (2005)
Isoperformance analysis	Method	Analysis				X	X			X	X			Quantitative method to balance performance against competing objectives of cost, risk, and other criteria	de Weck and Jones (2006)
Kano model	Method	Triage		X	X							X		Classification of product features/ functions into distinct levels of relevance	Reinhart et al. (1996)
LESS	Procedure model	All	X	X	X		X					X		"Large-scale scrum is a label – For brevity in writing – To imply regular scrum plus the set of tips that we have experienced and seen to work in large multiteam, multisite, and offshore agile development"	Larman and Vodde (2010)

(continued)

Table 1 (continued)

Name	Type	Involves activity	Volatility	Ambiguity	CompletenessI	CompletenessII	Feasibility	Integrability	Uncertainty	Solutionfixation	Optimality	Proliferation	Traceability	Description	Reference
Market research	Method	Elicitation		X	X									Systematic collection and analysis of needs and desires of individuals or organisations using statistical and analytical methods	Mooi and Sarstedt (2011)
MBSE	Tool	Specification		X		X	X	X			X			Model-based systems engineering is "the formalised application of modelling to support systems, requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases"	INCOSE (2020), Madni and Sievers (2018).
Mind mapping	Method	Elicitation		X	X									Creativity method to visualise connected terms in a structured way	Buzan and Buzan (1996)

Modelica	Tool	Specification		X										Object-oriented system description language	Fritzson and Engelson (1998)
Modelling and simulation	Method	Analysis				X	X		X	X	X			Computer-aided method to predict the behaviour and performance of a system	de Weck and Jones (2006)
Morphological chart	Method	Triage								X				Scheme to decompose requirements or functions	Pahl et al. (2007)
Need statements	Other	Elicitation		X	X									"A user need statement is an actionable problem statement used to summarise who a particular user is, the user's need, and why the need is important to that user. It defines what you want to solve before you move on to generating potential solutions […]"	Ulrich and Eppinger (2016)

(continued)

Table 1 (continued)

Name	Type	Involves activity	Volatility	Ambiguity	CompletenessI	CompletenessII	Feasibility	Integrability	Uncertainty	Solutionfixation	Optimality	Proliferation	Traceability	Description	Reference
Numerical optimisation	Tool	Analysis				X	X				X			Collection of tools to identify design variable values that maximise the performance of a design represented by a simulation model while satisfying requirements (expressed as constraints)	Papalambros and Wilde (2017)
OPM	Method	Specification		X								X		The object-process methodology provides a formal system modelling language	Dori (2011)
Pairwise comparison	Method	Triage										X		Determines the ranking of alternatives	Ramík (2020)
Personas	Other	Elicitation		X	X									"A persona represents an aggregate of target users who share common behavioural characteristics (i.e., is a hypothetical archetype of real users)"	Cooper (2004)

PMM	Method	Analysis				X								The property model methodology is a top-down approach building specification and design models of engineered systems	Micouin et al. (2018)
Product backlog	Method	Specification	X		X									"Product backlog is an evolving, prioritised queue of business and technical functionality that needs to be developed into a system"	Schwaber and Beedle (2002)
Prototype	Method	All		X	X	X	X	X				X		Physical or digital representation of an incomplete design for exploring, communicating, and evaluating its desirability, feasibility, and viability	Matthew et al. (1992)
QFD	Method	Analysis			X	X		X						Documentation scheme to translate the "voice of the customer" into technical requirements	Hauser and Clausing (1988)

(continued)

Table 1 (continued)

Name	Type	Involves activity	Volatility	Ambiguity	CompletenessI	CompletenessII	Feasibility	Integrability	Uncertainty	Solutionfixation	Optimality	Proliferation	Traceability	Description	Reference
Reference solutions	Method	Elicitation		X	X	X	X	X						Using prior knowledge about reference designs predecessor, reference designs, catalogues, guidelines	
Requirement list	Method	Specification		X	X	X							X	List of formal requirements	Pahl et al. (2007)
Scenarios	Method	Elicitation		X	X									"Providing context for trial use as well as for feed-back to designers. (user Centred design)"	Bodker (1999)
Scrum	Procedure model	All	X	X	X		X					X		A set of roles and ceremonies (daily stand-up, sprints, etc.) to realise agile development	Schwaber and Sutherland (2020)
Set-based design	Philosophy	Analysis					X	X	X	X	X			Considering several solution concepts simultaneously and slowly narrowing down the alternatives	Sobek et al. (1999)

Solution spaces	Tool	Analysis				X	X	X	X	X	X			Concept of all or a set of designs that satisfy a specified set of requirements. Can be computed by particular algorithms	Zimmermann et al. (2013)
Storytelling	Method	Elicitation		X	X									"Storytelling introduces a narrative element into designing, a description ofrelated events which link people over time"	Lloyd (2000)
SWOT analysis	Method	Elicitation		X	X									Planning tool that relies on a arranging strengths, weaknesses, opportunities, and threats to help identify strategic goals	Kotler and Keller (2006)
sysML	Tool	Specification		X								X		A collection of specified graphical elements to document systems with respect to requirements, functions, logic, and physical components and their relations	Matthew (2006), Friedenthal et al. (2014)
Uncertainty quantification	Tool	Analysis							X					Assess the effect of varying design variables on dependent variables	Peherstorfer et al. (2018)

(continued)

Table 1 (continued)

Name	Type	Involves activity	Volatility	Ambiguity	CompletenessI	CompletenessII	Feasibility	Integrability	Uncertainty	Solutionfixation	Optimality	Proliferation	Traceability	Description	Reference
User stories	Methods	Specification		X	X								X	"Short statements that describe stakeholder expectations"	Cohn (2004)
User story risk map	Method	Triage		X								X		Method to assess the risk of user stories used for general project management, prioritisation, or triage of user stories	Trauer et al. (2020)
Utility analysis	Method	Triage										X		Scheme to systematically rank alternatives using relative weighting and formalised assessment criteria	Friedman and Savage (1948)

Viewpoints	Method	Elicitation		X	X								“Viewpoint approaches aim to model the domain from different perspectives in order to develop a complete and consistent description of the target system. For example a system can be described in terms of its operation, implementation and interfaces”	Zowghi and Coulin (2005)
Volere	Tool	Elicitation		X	X								Template “for use as a basis for your requirements specifications.” used, e.g., in interviews	Robertson and Robertson (2000)

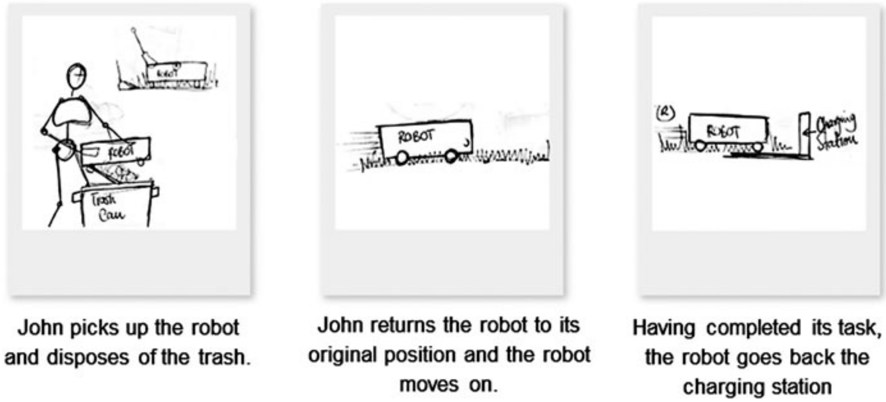

Fig. 8 Story board (excerpt) from a design project for a trash picking robot (courtesy ANGSA, angsa-robotics.com)

requirements documentation at play, such as the use of a unique identifier (ID number) and the use of engineering units (e.g., kilonewtons kN) (Fig. 11).

The systems modelling language **SysML** provides a set of modelling elements and diagrams; see Fig. 11, to relate requirements, functions, logic, and physical elements to each other. This enables comprehensive documentation and increases transparency and traceability. It is supported by many commercial tools and is often used in model-based systems engineering (INCOSE 2020; Madni and Sievers 2018) (Fig. 12).

The use of agile methods is increasingly popular in engineering. In the agile philosophy, the design is evolved gradually during so-called sprints which typically last anywhere between 2 and 4 weeks. The requirements in agile engineering are captured by so-called user stories in the form of "who wants what" and are linked to specific acceptance criteria and priorities which are voted on by the team and accepted (or not) by the so-called product owner. The effectiveness of the use of agile methodologies such as scrum for the development of hardware is the subject of ongoing research (Garzaniti et al. 2019).

An effective way to document the source of requirements in some fields like aerospace engineering is the use of a so-called concept of operations, **CONOPS**. The concept of operations is similar to a user story, but instead of focusing on individual consumers or users, it describes in graphical and textual form the major phases of a mission. The example shown here is the operation of a reconfigurable constellation of small satellites that can manoeuvre on orbit to take advantage of so-called repeating ground tracks which provide a high revisit frequency over observation targets of interest on the surface of the Earth. The major phases of the CONOPS for this mission are:

1. Launching the spacecraft into low Earth orbit (LEO), typically about 500 km altitude.
2. Transferring the spacecraft to a global observation mode (GOM).

After a long and productive day at work **BERND** needs to do something to stay healthy.
He feels bad about taking time for himself instead of for his family.

	Getting ready &on the way to work	Working Day at the office	Way to sport	Sport	Way back home
Action	1. Has breakfast with his family and is getting ready for work 2. Walks to tramstation 3. Comutes to work	8. Arrives at the office 9. Has meetings	14. Leaves the office 15. Takes public transport to the gym	19. Arrives at the gym 20. Workout	25. Leaves the gym and takes tram home 26. Arrives back home
Emotion / Thought	4. Another good day at work! 5. It always takes so long to get to the office 6. I wish I had my own car 7. The public transport is unreliable	10. I'm sitting all day 11. All days look the same 12. I enjoy moving around and stretching during lunch break 13. My back hurts more every day and I should do something about it	16. I am sick of crowded public transport after a long day at work 17. It takes so long 18. Is it okay to work out instead of spending time with the family?	21. I am working on my health 22. I feel so strong 23. I will have a shower at home 24. My back will be better by tomorrow	27. Oh it is late 28. Will my wife have cooked for me 29. I did the best for myself but there is no time left for my family

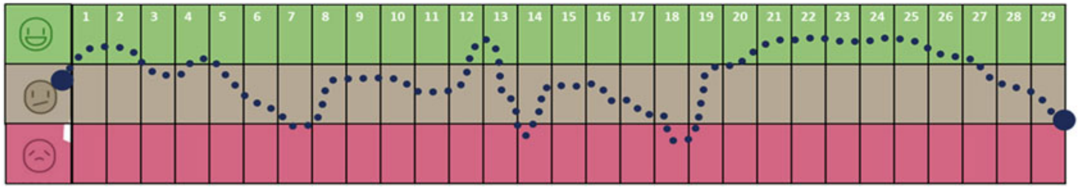

Fig. 9 Customer journey (excerpt) from a design project for a new mobility concept. (Courtesy BMW)

ID-Nr.	Description	Variable/ symbol	Lower limit	Nominal Value	Upper limit	Unit	Comment	Attachment	Origin/unit/ role name	Receiver unit/role/ name	Last update	priority	status
R1.2.1	Collapse load of deformation element	Fy	100		200	kN	Force range necessary to (1) prevent collapse of front rail by lower limit (2) Absorb sufficient energy by upper limit	s1002.xls	DCD-3 Dept. Crash Design/ front crash responsible small models / de Weck	DBD-4 Dept. Body Design/ front-end responsible small models / Zimmermann	25.2. 2021	1	accepted

Fig. 10 List of quantitative requirements (excerpt) for the crash structure of a vehicle

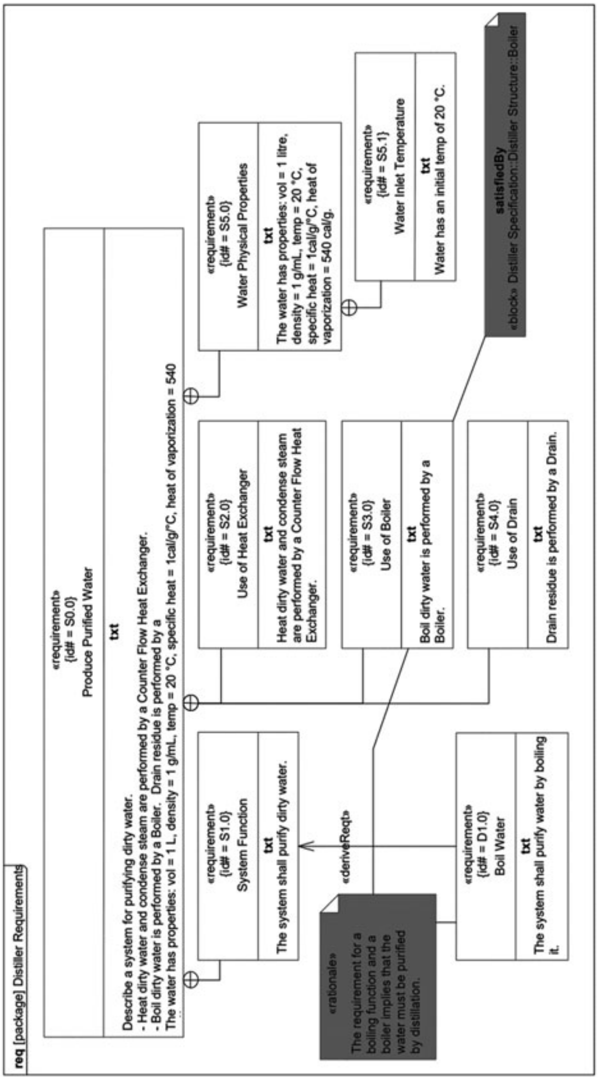

Fig. 11 SysML requirement diagram (Matthew 2006)

Sprint 1 (12.5.2017 - 26.6.2017)							
Prio	**Type**	**Name**	**Story**	**Acceptance Criteria**	**Done**	**Result**	**Responsible**
100	E	Separation of Shell and Beans	The farmer wants the bean (bean bundle) seperated from the rest of the pod	No shellparts in the bean bag No beans in the shell bag	No	Tests revealed that there have been no beans in the shell bag. However, some beans remainined inside the husks land in the shell bag.	Elif
100	E	Fabrication	The GIZ (customer) wants the machine to be fabricated in Cameroon with locally available resources	Material available in Cameroon Manufacturing possible with local resources	Yes	All parts are made of mild steel. The machine can be fabricated by the use of an angle grinder, a hammer and a welding device	Omar

Fig. 12 User stories in a backlog (excerpt) of a student design project for a cocoa pod peeling machine

3. Calibration of the onboard sensors such as cameras using known imaging targets.
4. Remote sensing of different points on Earth by transferring to a regional observation mode (ROM) in a so-called repeating ground track that favours one spot over others.
5. Deorbiting the spacecraft at the end of life to minimise issues with space debris.

In this graphical view of the mission life cycle, the phases or activities of the system should be read in clockwise fashion from the lower left to the lower right following the notional timeline (Fig. 13).

Once the concept of operations has been discussed and clarified with stakeholders, such as a funding agency, or commercial customer who is willing to pay for the service or resulting data products, it can be used as a source of requirements. Below is a sample of level 1 requirements for the ROAMS mission, including their underlying rationale (Table 2).

Requirements and specifications of a product that is supposed to meet these requirements can be collected in tender specifications and performance specifications, respectively (VDI 2519 2001): “The **tender specification** (German *Lastenheft*) describes all of the requirements from the point of view of the user including all of the ancillary conditions. These should be quantifiable and verifiable. The tender specification defines WHAT is to be done and for WHAT PURPOSE. The tender specification is compiled by the client or by commission of the client. It serves as a basis for the invitation for tender, offer and contract. The **performance specification** (German *Pflichtenheft*) contains the tender specification. It describes the user specifications in more detail and specifies the realisation requirements. The performance specification defines HOW and WITH WHAT the requirements are to be realised. It makes a definitive and concrete statement on the realisation of the material flow and automation system. The performance specification is generally compiled by the contractor after the order is granted and, as necessary, in collaboration with the client.”

Formulation Rules

When goals, expectations, desires, or needs are not explicit and are to be explored, focus should lie on understanding the stakeholder’s perspective rather than on preciseness and details. This is, for example, reflected in the formulation of user stories which are often expressed in the following form:

As a < role >, I want < some goal > so that < reason >.

This formulation includes the role of a known stakeholder or fictitious character, a *persona*. The more or less specific goal can be expressed using the first person to support empathy with the stakeholder’s perspective. A reason for this goal, representing an underlying need, may be included to encourage reflection about

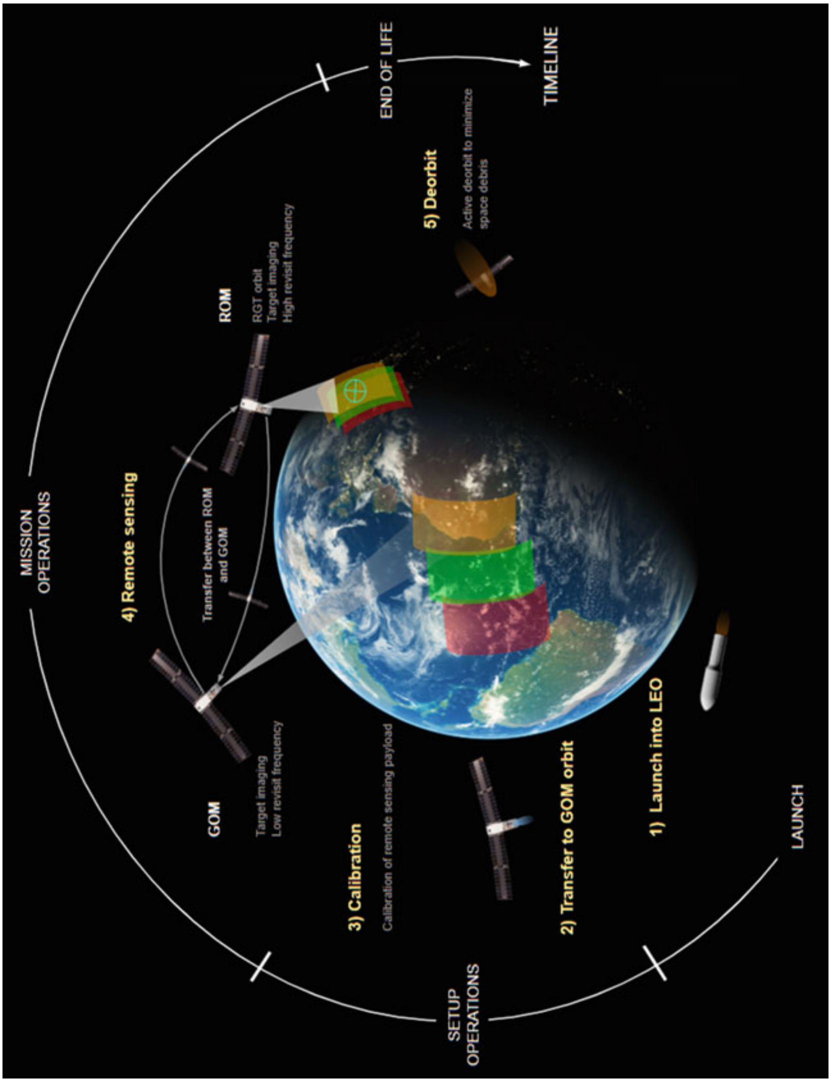

Fig. 13 Concept of operations (CONOPS) for the ROAMS (Reconfigurable on-Orbit Adaptive Maneuverable Satellites) mission (Chloe et al. 2021)

Table 2 Example of CONOPS for the ROAMS mission

Short text	Object text	Rationale
Number of targets (ROAMS)	The ROAMS spacecraft shall be able to visit at least 20 targets (each target requires 2 orbit transfer manoeuvres) between latitudes of +/− 51.6 deg. and over all longitudes during mission life	Visiting many targets over the mission duration allows for the identification of unanticipated problems and complexity. Observing many targets will serve as a risk-reduction step for future missions employing the reconfigurable constellation concept. If the satellite is deployed from the international space station (ISS), we will not be able to observe latitudes higher than the inclination of the ISS orbit (without costly inclination changes, which are not desired for this mission) Targets are not all known ahead of time
Number of manoeuvres (ROAMS-propulsion payload)	The ROAMS-propulsion payload shall be able to perform at least 3 orbit transfer manoeuvres	This is enough to demonstrate the feasibility of the concept
Science data – imaging	ROAMS shall collect science data for each of the target locations in the form of images taken in the VIS (R, G, B) + NIR bands and LWIR bands, taken both in the ROM and GOM configurations	In addition to accomplishing higher revisit frequencies, ROAMS shall demonstrate the benefit of the higher revisit frequencies in use cases – Which require science images
Science data – position	The ROAMS spacecraft shall include a GPS receiver for orbit determination (either in the bus or the ROAMS payload)	In addition to accomplishing higher revisit frequencies, ROAMS shall demonstrate the benefit of the higher revisit frequencies in use cases – Which require science images
Revisit frequency in ROM	ROAMS shall be able to observe a fixed ground target at a revisit frequency no less than once per sidereal day when in regional observation mode (ROM)	The utility of repeating ground track orbits is derived from their ability to position spacecraft for frequent revisits over a particular target. With a single satellite, one overpass per day demonstrates this utility sufficiently
Time for orbit transfer manoeuvre	ROAMS shall be able to perform transfer manoeuvres in less than 7 days	The changing of the spacecraft orbit is an important part in the ROAMS concept. An orbital transfer in less than 7 days ensures that at least 8 days will be devoted to taking target images

alternative goals that may equally satisfy the underlying need. The latter can avoid so-called requirements fixation (Mohanani et al. 2014).

When goals, expectations, desires, and needs are clear, focus should lie on preciseness to support a targeted development process for meeting these requirements. Rules for and examples of well-formulated requirements are listed in Table 3.

Quantitative Analysis Techniques

Importance of Quantitative Methods

Literature about requirements typically focuses on management aspects that are generally applicable and independent of the technical content. How to specifically address the aforementioned challenges for concrete design scenarios remains therefore often vague (Zimmermann et al. 2017). Consequently, producing concrete requirements bearing the characteristics listed in Table 3 remains a difficult task. Technical complexity in systems design can be addressed effectively using quantitative methods based on simulation and numerical optimisation – provided that simulation models are available.

Modelling and Simulation

One of the methods to address feasibility early during the requirements definition phase of a development project is the use of integrated modelling and simulation. Consider, for example, the following requirement: "The image centroid of the space telescope on the focal plane shall have a root-sum-square (RSS) jitter of no larger than 5 micrometres +/-5%" (de Weck and Jones 2006). This is a typical requirement for a telescope to prevent blurring of an image due to vibrations. Figure 14 shows a 5-second-high fidelity simulation that demonstrates that it is possible to reduce the jitter from about 15 micrometres (14.97 μm) to 5.20 μm, thus proving that such a requirement would be feasible and not utopian.

Isoperformance Analysis

Another perspective on the feasibility question for requirements is the notion of *isoperformance*. In this approach the design problem can be characterised by a Venn Diagram (Fig. 15, upper left) in an n-dimensional design space (meaning the number of design variables is *n)*, whereby within the set of bounded designs B, the set of feasible designs F is intersected with the set of isoperformance designs I and Pareto optimal designs P, to identify the set of efficient designs E that both satisfy the requirements, but are also efficient (non-dominated) in terms of the cost and risk objective space (de Weck and Jones 2006).

Table 3 Characteristics of well-formulated requirements

	Characteristic	Positive example	Negative example
Single requirements	Clear and unambiguous	The vehicle shall accelerate in 4 s from 0 to 100 km/h on a level paved road	The vehicle should be fast
	Verifiable (this often implies quantitative)	The structure of the aircraft shall not fail before 50,000 nominal flight load cycles	The structure of the aircraft shall never fail
	Feasible	The cost shall be reduced by 15% with respect to the previous product generation	The cost shall be reduced to 0
	Solution-neutral	The housing shall resist corrosion for 30 years	The housing shall be made of stainless steel
	As little restrictive as possible	The thickness shall be in the range of [1–2] mm	The thickness shall be 1 mm
	Covers seemingly obvious aspects	The blender's components shall be disassembled for cleaning in less than 1 min	The blender should be easy to clean
	Singular (actor-verb-object)	The coffee machine shall brew a cup of coffee within 15 s of starting the process	The coffee machine shall brew a cup of coffee within 15 s and should then automatically turn off
Sets of requirements	Non-redundant	The diameter shall be larger than 10 mm The diameter shall be less than 12 mm	The diameter shall be in the range of [10–15] mm The diameter shall be in the range of [8–12] mm The diameter shall be in the range of [9–14] mm
	Consistent	The diameter shall be larger than 10 mm The diameter shall be less than 12 mm	The diameter shall be larger than 10 mm The radius shall be larger than 24 mm
	Complete	The diameter shall be larger than 10 mm The diameter shall be less than 12 mm	The diameter shall be larger than 10 mm
	Without conflicts	The diameter shall be larger than 10 mm The diameter shall be less than 12 mm	The diameter shall be less than 10 mm The diameter shall be larger than 12 mm

In this sense, the requirements on performance are used to set a target zone (Fig. 15) (c) as well as constraints in the design space (b) in order to identify satisficing designs that may be acceptable to the stakeholders while each representing different trade-offs in terms of cost and risk of product development.

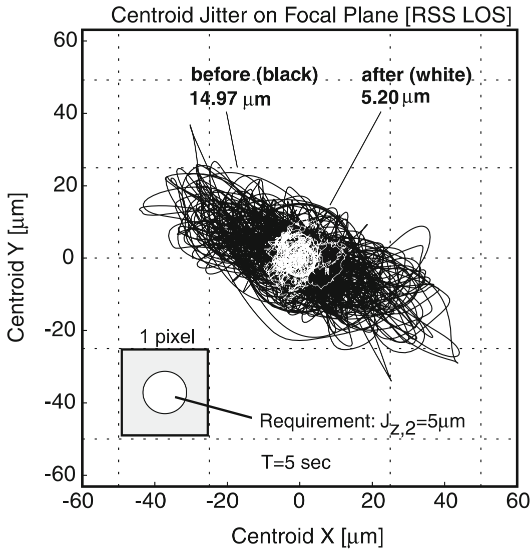

Fig. 14 Root sum square (RSS) line of sight (LOS) pointing requirement for a space telescope in terms of image motion on the focal plane (de Weck and Jones 2006)

Problems with requirements feasibility arise when the reachable region shrinks to be zero or is too small or overly ambitious performance targets are set outside the reachable region.

Target Cascading and Solution Space Optimisation

Target cascading and solution space optimisation are particularly relevant for breaking down (or decomposing) quantitative requirements into several requirements for different stakeholders. Quantitative requirements are formulated for *quantities of interest* that measure the performance of a part of a product, e.g., y_j for stakeholder X in Fig. 4.

When quantitative models are available, requirements on quantities of interest can be broken down into requirements on design variables. In **analytical target cascading** (Kim et al. 2003)**,** this is done solving an optimisation problem where the objective and constraint functions are formulated using quantities of interest. The resulting values for design variables represent an optimal solution. They serve as *target values* for requirements on the lower-level design problem.

In a similar approach, requirements for the lower-level design problem are formulated as a set of *target ranges*, so-called **solution spaces**; see Zimmermann et al. (2013). The particular challenge here lies in identifying ranges for many design variables that are both as large as possible to provide design freedom and sufficiently narrow to avoid combinations of design variable values representing an infeasible or unacceptable design, i.e., a design that violates superior requirements.

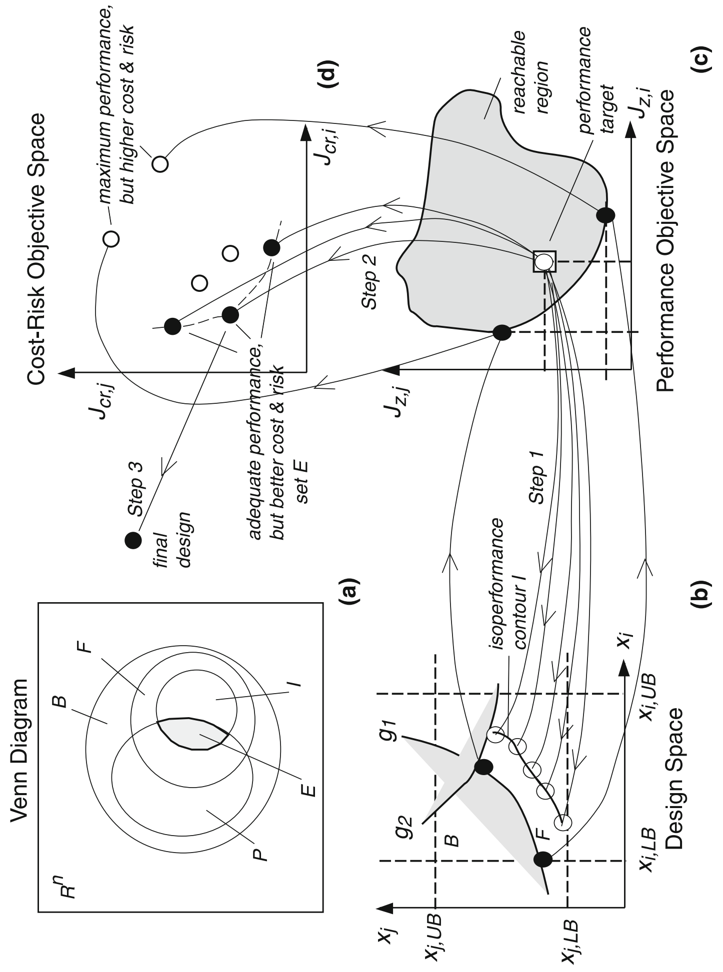

Fig. 15 Isoperformance approach to early feasibility assessment of requirements (de Weck and Jones 2006)

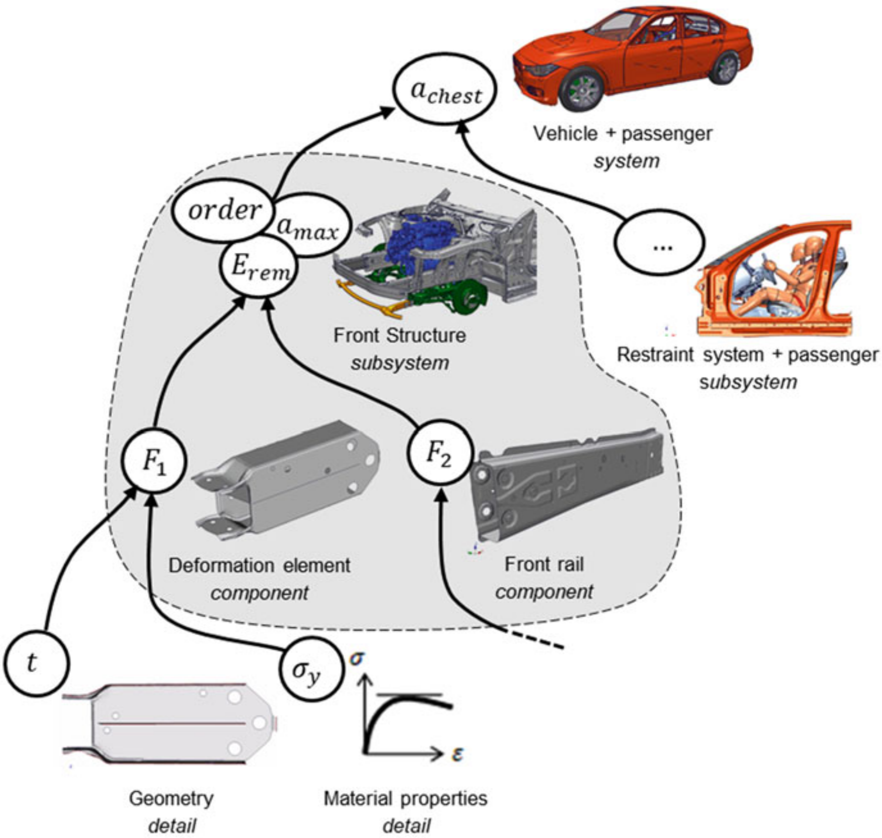

Fig. 16 Description elements organised in a hierarchical dependency graph for a vehicle front crash (excerpt, courtesy BMW)

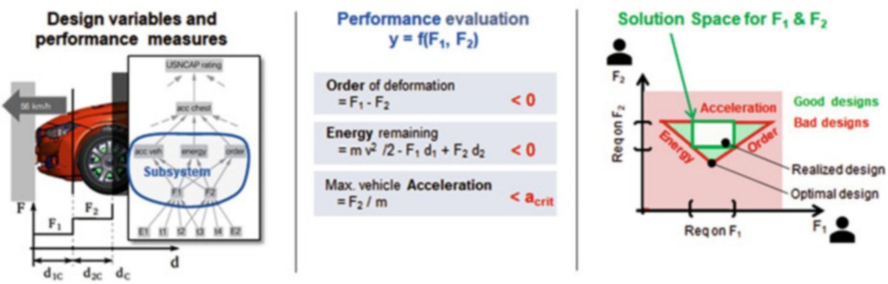

Fig. 17 Breaking down requirements on the vehicle structure into requirements on two sections. (Courtesy BMW)

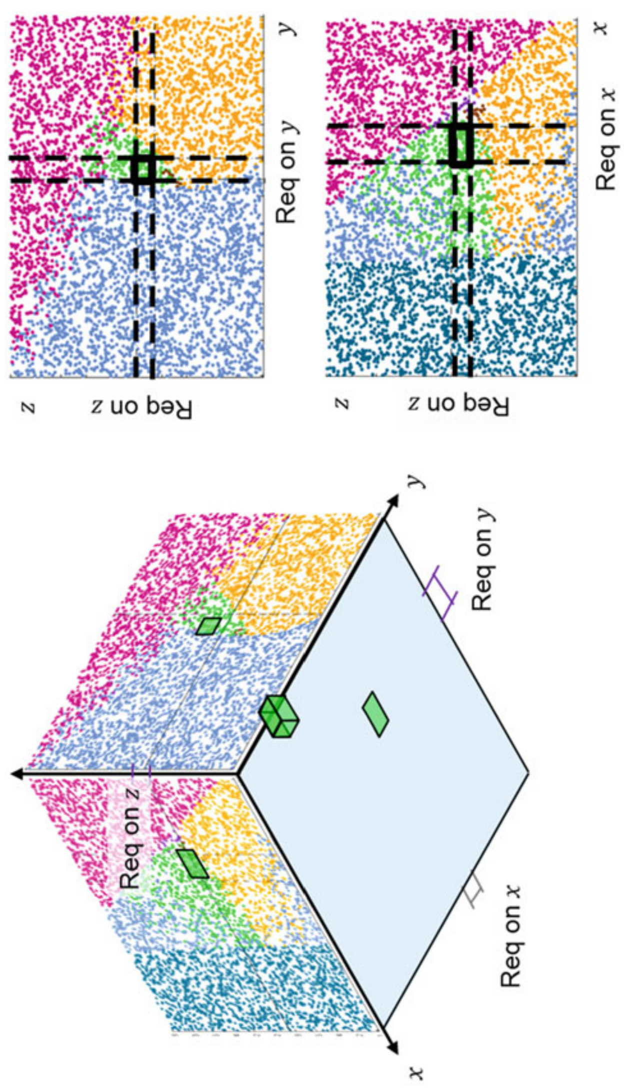

Fig. 18 A solution space visualised by 2D projections serving as interval requirements on the description elements x,y,z

Figure 16 illustrates an example where quantitative requirements on the system (road vehicle with passenger in a front crash) are broken down into requirements on two subsystems (front structure and restraint system with passenger) and then into requirements on components (deformation element and front rail), and finally into requirements on detailed design variables. These three steps can be considered as three distinct design problems where a solution is generated by narrowing down the permissible range of product properties. Each design problem may be assigned a different stakeholder such as a system designer, a subsystem designer, and a component designer. The dashed line in Fig. 16 defines the scope of the second design problem and the range of interest of the subsystem designer: They will receive requirements on the quantities of interest *order* (of deformation of components), E_{rem} (remaining energy when components have reached maximum deformation) and $a_{\max}$ (maximum acceleration during deformation). Then, requirements on the design variables F1 and F2, representing collapse loads of structural members, are to be formulated such that the requirements on the quantities of interest *order* E_{rem} and $a_{\max}$ are satisfied. For this, Fig. 17 shows a simple yet representative example: analytical target cascading would produce a design on the F1-F2-plane that minimises one quantity of interest ($a_{\max}$) while satisfying requirements on the others ($order < 0$, $E_{\mathrm{rem}} < 0$), denoted as *optimal design*. By contrast, the solution space in the F1-F2-plane provides target intervals for each design variable on which the superior requirements are satisfied. In other words, it provides more design freedom and is robust with respect to unintended deviations from an intended target state.

An illustration of how three-dimensional solution spaces are visualised by two-dimensional projections is shown in Fig. 18. This can be scaled up to an arbitrary number of dimensions.

Conclusion

The Roman philosopher Lucius Annaeus Seneca paraphrased the need for direction by saying that “If one does not know to which port one is sailing, no wind is favourable”. Requirements have been considered an important tool for providing direction in systematic design since the early days of design theory. More modern design philosophies, like agile approaches, expanded their static use to enable more flexibility to better cope with the increasing complexity of engineering systems. The necessity of adapting form and extent of requirements to the design context and updating requirements possibly several times during a design project is now widely recognised and accepted. However, this has not diminished their relevance for providing structure and orientation.

Stakeholder expectations are expressed by requirements. Needs of society are considered in engineering systems by casting regulations into requirements. Requirements management coordinates and aligns different views and interests of stakeholders. Therefore, it is to a large extent a social activity relying on communication and empathising.

The authors predict that the importance of requirements formulation and management will further grow with increasing complexity in our world. One approach to cope with complexity is to incorporate it into models. Accordingly, there is a trend to build ever larger simulation models and use ever more data in engineering. Models become more complex and predictive, leading to so-called digital twins. This is useful for eventually understanding engineering systems in a *scientific* sense. The opposite though, i.e., decomposing systems and models thereof into manageable pieces to reduce size and complexity (possibly enabled by the improved understanding through more complex models), will remain key to successful *engineering*. And this will be driven by requirements.

Cross-References

- ▶ Architecting Engineering Systems: Designing Critical Interfaces
- ▶ Data-Driven Preference Modelling in Engineering Systems Design
- ▶ Design Perspectives, Theories, and Processes for Engineering Systems Design
- ▶ Dynamics and Emergence: Case Examples from Literature
- ▶ Engineering Systems Design Goals and Stakeholder Needs
- ▶ Engineering Systems Design: A Look to the Future
- ▶ Engineering Systems Integration, Testing, and Validation
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16 Designing for Human Behaviour in a Systemic World

Anja Maier and Philip Cash

Contents

Abstract

This chapter addresses designing for human behaviour in a systemic world. Many theories and examples of behavioural interventions are available to designers today, from fields spanning the natural, social, behavioural, health, and technical sciences. This chapter provides an overview and synthesis of approaches, as well as guidance through this landscape for designers. Literature is reviewed from two perspectives: (i) 'technology-first', where technology is the primary driver of

A. Maier (✉)
Department of Technology, Management and Economics, DTU-Technical University of Denmark, Kongens Lyngby, Denmark

Department of Design, Manufacturing and Engineering Management, University of Strathclyde, Glasgow, UK
e-mail: amai@dtu.dk

P. Cash
Department of Technology, Management and Economics, DTU-Technical University of Denmark, Kongens Lyngby, Denmark
e-mail: pcas@dtu.dk

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design, and (ii) 'human-first', where it is human behaviour that is the driver and focus. Further, the review covers three main levels of intervention: (i) individual or micro-, (ii) group or meso-, and (iii) societal- or macro-level. Perspectives and levels are synthesised via a 'design as connector' lens, bridging insights ranging from engineering to policy. Based on this synthesis, it is shown that in order to create and sustain change in a systemic world, designers need to consider combinations of interventions across multiple levels that work together in both the short and longer term. We encapsulate this into four main points of guidance, illustrated by examples from health behaviour, sustainable behaviour, and urban planning. Collectively, this opens new directions for engineering systems design researchers and provides practitioners with practical guidance for navigating this complex landscape.

Keywords

Behavioural design · Design for behaviour change · Engineering systems · Engineering systems design · Human behaviour · Intervention design · Social design

Introduction

Human behaviour can be broadly defined as 'anything a person does in response to internal or external events' (Michie et al. 2014b), and behavioural understanding relates to any stakeholder. Thus, in an increasingly interconnected world, designing for human behaviour means thinking in systems (Meadows and Wright 2008; Tromp and Hekkert 2018).

Our behaviour is both affected by and affects the technical and social world around us (Papanek 1972; Fuller 2008). Assumptions about people's behaviour are embedded in the world, encoding with every piece of technology, process, or societal interaction, an explicit or implicit hypothesis about human behaviour at some scale (McLuhan and Lapham 1994). For example, when designing for society, we encounter legacy considerations (Tromp and Hekkert 2018; De Weck et al. 2011) and as such, do not design from scratch but rather intervene and redesign technologies, processes, behavioural patterns, and societal interactions. However, this scope poses major questions in terms of how designers should understand and work with human behaviour.

A growing body of research across the humanities and social, technical, and natural sciences is devoted to the study of human behaviour and behaviour change. While work on designing for behaviour change has expanded substantially in recent years, research has typically focused on interventions at specific levels, ranging from individual to societal, often treated separately. Moreover, while there are a number of systematic and scoping reviews of theories, strategies, heuristics, taxonomies, tools, techniques, and examples of behavioural interventions from various fields, a comprehensive overview and synthesis of approaches inclusive of navigational guidance through this landscape is missing.

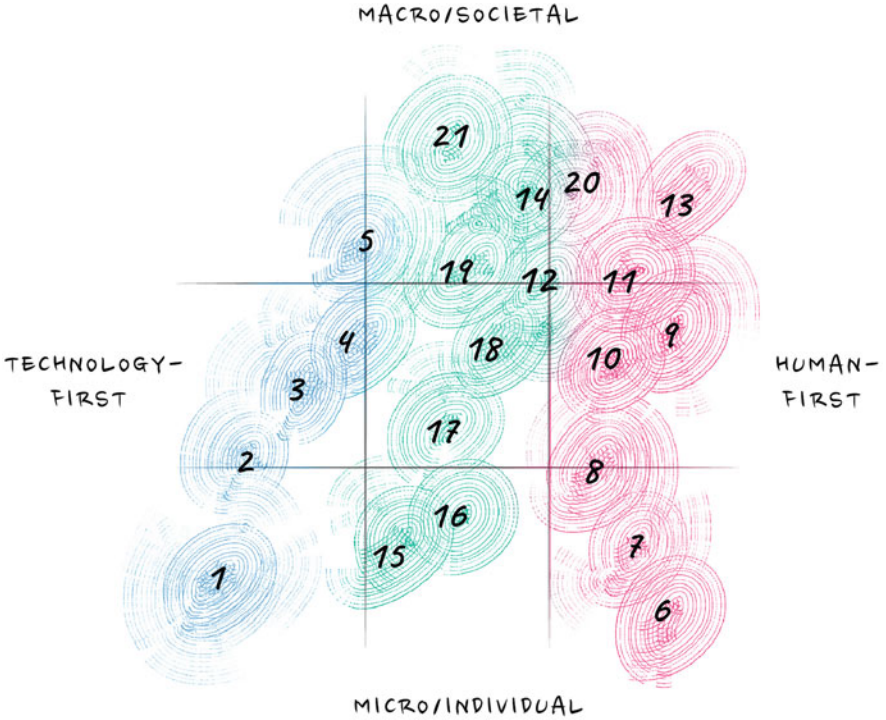
This handbook chapter provides an overview and synthesis of the state of the art in designing for human behaviour in a systemic world. We first examine this challenge from two essential perspectives, technology-first and human-first (section "Introduction"), before linking them via a multilevel conceptualisation of engineering systems design (section "Understanding and Designing for Human Behaviour: Perspectives and Levels"). We then discuss how designers can navigate this landscape and provide guidance for effective design in this context, using examples from health behaviour, sustainable behaviour, and urban planning (section "Navigational Guidance for Effective Interventions").

Understanding and Designing for Human Behaviour: Perspectives and Levels

There are many perspectives on human behaviour. Behaviour is taken both as informing technical (re)designs and constituting an effect, e.g. in design for behaviour change (Cash et al. 2017) or in social design (Tromp and Hekkert 2018). Current perspectives in literature on designing interventions for systemic change have, at their starting point, the aim to understand and positively support behaviour change via interactions with technologies and other humans. As such, these can be organised along a human-technology axis (Subrahmanian et al. 2018), as in Fig. 1.

The 'technology-first perspective' highlights that when attempting to make designs more human-friendly, improve human performance, or reduce human error, questions of usability, reliability, and safety come to the fore, i.e. behaviour with respect to technology. As such, the starting point is with the technology, where 'the human factor' has to be taken into account. In contrast, the 'human-first perspective' highlights that when attempting to understand and design for behaviour, questions of human change come to the fore, i.e. technology with respect to behaviour. As such, the starting point is with the behaviour, where the technology becomes a facilitator. Typically, engineering theory focuses on 'technology-first' with humans as users, such as operators, while behavioural theory focuses on 'human-first' (Khadilkar and Cash 2020).

Critically, designing is typically positioned at the intersection between these two perspectives (e.g. Cross 1982: 223; Dorst 2019: 119), connecting and bridging the two by treating the human and the technological as symbiotic. This bridge develops at three distinct yet interconnecting levels, from the individual person and technological artefacts or services, through group 'embeddedness' and more complex and advanced systems, to the societal context and surrounding sociotechnical systems, in other words, a micro-level, the level of interacting individuals; a meso-level, the level of communities and institutions; and a macro-level, the level of entire societies. When designing for behaviour, interventions create ripples across levels and hence point to the need to navigate the whole landscape in order to develop robust interventions. However, before we address this issue of navigation, we will first establish the major axis and design landscape illustrated in Fig. 1.



1. Human in the Loop Technology (HITL); 2. Human Computer Interaction (HCI);
3. Cognitive (systems) engineering; 4. Human Factors Engineering (HFE);
5. Human Systems Integration (HSI); 6. Prospect Theory, Nudge Theory;
7. Theory of Reasoned Action (TRA); 8. The Transtheoretical Model (TTM);
9. (Social) network theories; 10. Social norms, social influence;
11. Theories of organisational change; 12. Diffusion of Innovations Theory;
13. Social movements, crowd behaviour; 14. Whole Systems Change (e.g. Multi-Level Perspective, MLP); 15. User experience / User interface design (UX, UI);
16. Persuasive design (e.g. Fogg Behavioral Model, Design with Intent); 17. Design for sustainable behaviour; 18. Design of services and interactions (e.g. servitisation);
19. Re-framing (e.g. Frame Innovation, Transition Design); 20. Social design (e.g. designing for society / social impact design); 21. Policy design, design for policy and governance.

Fig. 1 Designing for human behaviour – synthesising research on human behaviour in the context of engineering systems design. This includes the perspectives (technology-first (blue), human-first (red), design as connector (green)) at three levels of intervention (micro/individual, meso/group, macro/societal). (Figure drawn with assistance from Andrea Bravo)

Technology-First

From a technology-first perspective, it is technical designs or technical behaviour that approaches are focusing on. While interlinked, here, the area of solution is predominantly the technology and the area of effect is predominantly (on) the human (Züst and Troxler 2006). However, the way in which various stakeholders are incorporated into the design process during complex engineering projects and the degree of emphasis on human behaviour varies. Overall, there has been a development in the degree of consideration given to human's interaction with technologies from the small scale 'human as a component', the mid-scale 'human as a source of error' affecting certain system elements, to the whole systems scale 'human as a partner'.

With this in mind, we examine literature from across human-technological systems interaction, where the term 'system' means technology. This includes the fields of (technical) *systems engineering* (SE), *human-computer interaction* (HCI), *human factors engineering* (HFE) and cognitive (systems) engineering, and *human-systems integration* (HSI).

Accounting for the Human Component

With traditional systems engineering, as applied to technical systems (in the literature also named technological or engineered systems), such as spacecraft and aircraft design, the main goal has been to solve a technical problem (INCOSE 2007; Kapurch 2007; Buede 2008). Consequently, these approaches have focused on technological systems, hardware, and software components. People are considered at the 'micro-level', in the sense that most technological systems also include 'humanware'. Here, humans are just one 'element' or 'component' in the system that needs to be accounted for (Jackson 2010), e.g. in the role of operators. The main question asked has been: How might we engineer (technological) systems that account for humans, i.e. are usable by humans?

Accounting for human behaviour is embodied, e.g. in the concept of *human in the loop* (HIL) or *human in the loop technology* (HITL), which traditionally refer to a model where interaction with a human is required (Karwowski 2006), e.g. in operating a technology. For interfacing with humans, or 'bringing humans into the loop', a host of (computational) modelling and simulation methods are used. Mainly in the context of use of technical systems and as decision support through cognitive and motor skills training. For example, HITL is often referred to as interactive simulation, which is a special kind of physical simulation that includes human operators, such as in flight or driving simulators. Human in the loop simulations may include training of motor skills (e.g. flying an airplane), cognitive or decision-making skills (e.g. committing fire control resources to action), or communication skills (e.g. as members of command and control centres). Virtual simulations, envisaging scenarios, and measuring performance are used, for example, in logistics, supply chains, or the training of power plant operators or aircraft pilots. Thus, in this conceptualisation, consideration focuses on specific human-artefact interactions, which constrain the design space to behaviour at the micro-level.

Preventing Human Error and Increasing Human Performance

Expanding on the above, research on accidents during World War II highlighted how technologically advanced, complex, powerful, and faster machines surpassed operators abilities (Wickens and Kessel 1981), leading to system failures attributed to human error (Reason 1990). This resulted in a continued focus on technical aspects of design, but with a broader goal to deliver reliable, productive, safe, comfortable, and effective human use of tools, machines, systems, and environments (Sanders and McCormick 1993; Norman 1988). Here, humans are considered at the 'meso-level' in terms of their interaction with numerous parts of the system but still ultimately with respect to specific subsystems. The main question asked has been: How might we design to prevent human error or increase human performance?

This broader goal is associated with an increased emphasis on the importance of understanding both physical and psychological human limitations in the operation of technologically advanced systems, embodied in *human factors and ergonomics (HFE)*. This was supported by work on 'human behaviour, abilities, limitations and other characteristics' (Sanders and McCormick 1993: 5). This includes, for example, functional allocation (e.g. what aspects of robotic interaction require human inputs), task analysis (e.g. identification of specific tasks a workstation will be used to perform and the steps required for completion of each task), design and prototyping (e.g. collaboration with CAD modellers, engineers, and developers), and user testing (e.g. putting prototypes through use case scenarios to improve and revise the design), all around specific areas of interaction such as graphical user interfaces. This integrated biomechanical considerations, assessment of mental workload, attention demands, and usability of the technology system (Norman 1988). Further, it expanded the scope of human factors, to *human-computer interaction* (HCI) with a focus on software and human cognitive issues. This necessitated designing technologies, computerised systems, and their interfaces, with the intent to accommodate both human's physical and cognitive limits (Wilson et al. 2013; Hollnagel 2003). While such issues have generally been discussed in terms of usability in response to observed problems, recent work also highlights the need for human factors to be considered proactively (Rasmussen 2000). Thus, in this conceptualisation, consideration focuses on the wider interaction between humans and systems of artefacts at the meso-level.

Towards Human-Technological Systems Integration

With the goal of delivering simultaneous human and technological performance, *human-systems integration* (HSI) considers interactions between humans and systems to make sure system demands are within the capabilities of its users at the 'macro-level', i.e. throughout the system development process as a whole (Booher 2003; Kapurch 2007; Boy 2020; Schwartz et al. n.d.). In particular, HSI is concerned with coordination and integration across the system life cycle, ensuring that the characteristics of people are considered throughout the system development process, for example, with regard to their selection and training, their participation in system operation, and their health and safety (National Research Council 2007). This includes issues of human resources, personnel, training, human factors engineering, safety, health, and survivability. Here, humans are considered at the macro-scale in terms of their interaction as part of, and with, the whole technological system. The main questions asked have been: How might we bring relevant stakeholders into design and development as an ongoing process? How might we bring stakeholders together right from the start? How might we provide tools and methods to support the system development process itself?

The aim to integrate humans into technical system design has at its core the reduction of risk and life cycle cost and demands that human capabilities and needs be considered early and throughout system design and development (National Research Council 2007). Unpacking this, we must go beyond traditional technical systems engineering and consider more recent advances in information and social systems. Here, one example is the T53 Helicopter Engine where HSI built in early and continuous involvement of major stakeholders led to key improvements in the engine as well as the wider technical system, including human work processes, training requirements, maintenance, and ultimately costs. HSI has been said to help move business and engineering cultures towards a more holistic people-technology orientation (Booher 2003). In this evolution from technology-centred engineering to human-systems integration, recent proposals have been made for a view of HSI as simultaneously being technology-centred and human-centred (Boy 2020), i.e. human as a partner. Linking this to the latest advancements in automated decision support (e.g. healthcare robots and autonomous vehicles), there is a gradual empowerment of the human and at the same time a multifaceted dialogue on the ethics of artificial intelligence (Bird et al. 2020). In an interactive machine learning context, for example, this implies a hybrid computation model whereby humans can intervene to overrule decisions taken by a technological system. This becomes more important, the higher the cost of a mistake. As such, human-system interaction grows increasingly important and accessible to designers as technological systems integrate more and more smart elements. Thus, in this conceptualisation, interaction between humans and technological systems is treated as a whole at the macro-level, with the associated complexity and emergent properties.

Reflecting and Concluding on the Technology-First Perspective

In going forward, from a technology-first perspective, we see visual attention and social processes in team settings, and end user human-visualisation interfaces and computational data analytics coming to the fore (Ploderer et al. 2014). Further, there are increasing calls for awareness of ethics and the values underlying algorithms, going beyond (merely) human in the loop to empowering end users (Shih 2018). This is of particular significance in the face of increasingly powerful artificial intelligence (AI) (Amershi et al. 2014), where technological systems that can learn interactively from their end users are quickly becoming widespread.

Ultimately, we see an overall movement towards placing humans at the core when developing technological systems, rather than considering them as users of systems ‘only’. In other words, we see an overall movement from a focus on developing technology that has to function to being more efficient through reducing human error to a focus on designing with the human in mind from the start; from human in the loop at the micro-level to human as equal partner at the macro-level.

Human-First

From a human-first perspective, it is humans and human behaviour that approaches are focusing on. Here, human behaviour is the focus of theory, the area of intervention, and the area of effect (Züst and Troxler 2006). Across scientific disciplines and application domains, literature on human behaviour and behaviour change distinguishes between the levels at which interventions act. While the specific terms for each level vary, a three-level distinction is common (e.g. Michie et al. 2013; Kok et al. 2016): a micro-level, the level of (interacting) individuals; a meso-level, the level of communities and institutions; and a macro-level, the level of entire societies. Here behaviour has multiple influences ranging from intrapersonal (biological, psychological) and interpersonal (social, cultural) to physical environmental and public policy. Overall this leads to a complex systems lens on intervention development (Moore et al. 2019) (for more details see also section "Navigational Guidance for Effective Interventions" in this chapter).

With this in mind, we examine literature from across fields, drawing mainly from the social sciences. This includes behavioural economics and choice architecture, computational social science and networks, innovation, sociology, and organisation studies with diffusion, collective behaviour, and whole systems change.

Individuals and Reasoning

At the micro-level, design relevant frameworks and theories of behaviour change typically focus on the individual and their characteristics. This includes, for example, knowledge, attitudes, beliefs, and personality traits (Glanz and Rimer 2005), as well as models of why and how people act sometimes also against their own best interests (Festinger 1962). Here, individual behaviour is taken as the major vector for change, with individual changes paving the way to, for example, institutional or societal change. In particular, this approach is evident in health (Tombor and Michie 2017), energy, and environmental policy (Hampton and Adams 2018). The main questions asked have been: What behaviours can be made easier if certain factors are altered, e.g. laws, regulations, distribution, and offerings? What lessons can be learned for the design of other choices around desirable changes?

Human behaviour at this level has been discussed extensively in psychology and behavioural economics and includes a huge array of models, as reviewed by Michie et al. (2014a). Therefore, we highlight a selection of theories particularly relevant to designers, including prospect theory (Kahneman and Tversky 1979) and nudge theory (Thaler and Sunstein 2008), the theory of reasoned action (Ajzen and Fishbein 1980) and theory of planned behaviour (Ajzen 1991), and the transtheoretical model (Prochaska et al. 2005).

First, prospect theory examines the 'predictably irrational' ways that we humans behave (Kahneman and Tversky 1979; Kahneman 2011). Kahneman and Tversky pose that humans have *at least* two reasoning systems – system 1 and system 2 – with corresponding types of processing, type 1 and type 2, which work in parallel. Type 1 is fast, involuntary, and intuitive, whereas type 2 is more deliberate and rational. This model provides a basis for understanding many well-known cognitive biases such as the anchoring effect, or risk aversion, as well as how individuals use heuristics when making choices. Operationalising this for human behaviour change in engineering systems design by building on the idea of 'heuristics and biases' in decision-making (Kahneman and Tversky 1979) is nudge theory (Thaler and Sunstein 2008) or 'nudging'. Here, a nudge is any aspect of the choice architecture (i.e. the practice of influencing choice by 'organizing the context in which people make decisions' (Thaler et al. 2013: 428)) that alters people's behaviour in a predictable way without forbidding any options or significantly changing their economic incentives (Thaler and Sunstein 2008: 6). Rather than forcing us to do things, choice architecture is the act of designing choices in such a way that individuals will be steered (or 'nudged') towards more healthy or socially beneficial behaviour, for example, by putting fruit at eye-level to encourage healthy eating. Such dual-process models thus provide designers with key insight into how behaviour can be understood and influenced.

Second, and in contrast to prospect and nudge theory, is the theory of reasoned action (TRA) (Ajzen and Fishbein 1980). This theory suggests that a person's behaviour is determined by their intention to perform the behaviour and that this intention is, in turn, influenced by their attitude towards the behaviour and subjective norms. If people evaluate the suggested behaviour as positive (attitude) and they think valued others want them to perform the behaviour (subjective norm), this results in higher intention (motivation), and they are more likely to do so (behaviour). This formed the basis for the theory of planned behaviour (TPB) (Ajzen 1991), which examines the relations between an individual's beliefs, attitudes, intentions, behaviour, and perceived control over that behaviour (Ajzen 1991). With the inclusion of perceived control over a certain behaviour, i.e. incorporating specific skills or external facilities, the TPB has been used to underpin various kinds of strategies to change behaviour or lifestyle. For example, with the intention to recycle, collection systems need to be available and understandable. However, even with the inclusion of perceived behavioural control, caution has been voiced as behavioural intentions do not always lead to actual behaviour. Nonetheless, the TPB provides several concrete vectors for influencing behaviour.

Finally, the transtheoretical model (TTM) (also called stages of change model) describes individuals' motivation and readiness to change occurring as a process over time (Prochaska et al. 2005). This model focuses on the decision-making of the individual and their intentional change. It operates on the assumption that humans do not change behaviours quickly. Rather, change, especially of habitual behaviour, occurs through a cyclical process with six stages: pre-contemplation, contemplation, preparation, action, maintenance, and termination. For each stage of change, different intervention strategies are relevant and effective (Glanz and

Rimer 2005). For example, in a public health context, strategies addressing citizens or patients at different stages in their decision-making might include a tailored programme that is specifically created for a target population's level of knowledge and motivation. The model has been applied, e.g. to exercise behaviour or adherence to medication processes such as self-care in controlling diabetes and its complications (Kavookjian et al. 2005). Thus, the TTM provides an important temporal perspective, complementary to the other models mentioned in this section.

Despite differences in focus, all of these theories deal primarily with the individual and hence implicitly – from a design perspective – individuals' interaction with technologies. Thus, in this conceptualisation, consideration focuses on interaction between humans and artefacts at the micro-level.

Groups and Connections

At the meso-level, design relevant frameworks and theories of behaviour and behaviour change typically focus on interventions targeting groups or smaller networks of humans. Here, behaviour emerges from the connections and interactions between humans (e.g. Lehmann and Ahn 2018). The main questions asked have been: How do social networks influence people's knowledge and practice? How can social networks be influenced? What dimensions (knowledge, attitudes, perceptions) of behaviour/social change can be promoted through networks?

Human behaviour at this level has been discussed extensively in network science, sociology, and organisation studies. Again, we highlight a selection of theories particularly relevant to designers, including network theories and methods (Wasserman and Faust 1994; Borgatti et al. 2009; Barabási 2002), social norms (Hechter and Opp 2001), and theories of organisational change (Sullivan 2004; and for overview (Hayes 2018)). Here, each theory provides a different way of describing network structure, and ways of understanding spreading behaviour, also called propagation paths, cascading, or diffusion behaviour.

First, network theories examine how network structures (e.g. centrality) and processes over the network (e.g. spreading behaviour) influence social behaviour and dynamics (e.g. Granovetter 1973; Barabási 2002), ranging from political opinions, to weight gain, or happiness (Christakis and Fowler 2007). To effect change, i.e. influence (complex) spreading phenomena in social systems (Lehmann and Ahn 2018), (social) network studies advocate a focus on the connections (i.e. edges) between nodes (e.g. people). Connections can include kinship, friendship, or information flow (Monge and Contractor 2003), advice (Kilduff and Tsai 2003), or communication and geographical movement patterns (Stopczynski et al. 2014). For example, understanding people's movement patterns indicate mobility that affects urban planning, traffic forecasting, epidemic prevention, emergency response (González et al. 2008), and spread of infectious diseases (Klovdahl 1985; Bradley et al. 2020). Here, three main properties have been found to increase spread: (i) focusing on weak ties (Granovetter 1973), i.e. ties beyond close friends and family; (ii) 'small world' structure (topology) (Watts and Strogatz 1998), where ties connect otherwise distant nodes, dramatically increasing propagation across a network by creating 'shortcuts' between remote clusters; and (iii) scale-free degree distributions (Barabási 2009), where the characteristics of a network are independent of its size. Thus, aspects of network structure and dynamics can help designers understand and influence propagation paths in the face of complex situations involving many interconnections and emergent patterns of collective behaviour.

Second, critical to understanding the link between individual cognition and the behaviour of the wider group are the emergence and influence of social norms (Cialdini et al. 1990). Social norms are based on the rules that a group uses to discriminate between appropriate and inappropriate values, beliefs, attitudes, and behaviours. Social norms may be explicit or implicit, and failure to conform can result in social sanctions and/or social exclusion. They have been extensively studied in the social sciences with particular attention being paid to the conditions under which norms are obeyed, as reviewed by Bicchieri and Muldoon (2011). For example, works in anthropology describe how social norms emerge in different cultures; works in sociology how norms motivate people to act; works in economics how adherence to norms influences market behaviour; and works in law how they provide signalling mechanisms and alternatives to legal rules. Perceived norms are the result of individuals interpreting and perceiving values, norms, and attitudes that others around them hold and represent an emergent, collective code of conduct. They are reinforced through routine group approval and can be shaped by designed interventions. Thus, being cognisant of social norms helps engineering systems designers in anticipating potential reactions to interventions.

Third, in addition to general social theories like the above, a large amount of behaviour occurs and is shaped by formal organisations – including schools, businesses, or government. As such, we finally highlight theories of organisational change (for an overview, see Hayes 2018). They help explain how an organisation may influence behaviours via its structure of programmes and services, potential resistance to change, how to translate the need to change into a desire to change, and how change is implemented (e.g. (Lewin 1947; Kotter 1995; for a review, see also By 2005)). For example, organisations must strike a balance between stability and change. While a focus on stability, hierarchy, and predictability may discourage change, the need for renewal, survival, and consolidation may encourage change. Here, whole systems organisational change (Ackoff 1974; Weisbord and Janoff 1996) is a type of large-scale intervention to accomplish transformational – radical and fundamental – change in an organisation. While there are a variety of approaches to accomplish whole systems change in an organisational context (see reviews by (Maes and Van Hootegem 2019) and (Weick and Quinn 1999)), these generally seek to involve all stakeholders in the intervention and, where that is not possible, representatives. As such, theories of organisational change complement the prior models in this section by providing insight into the concrete management of change over time.

Collectively, these theories form a foundation for understanding how designed interventions can help direct human behaviour through its interaction with wider structures, such as social networks, social norms, or formal organisations. Thus, in this conceptualisation, consideration focuses on broader interactions between multiple humans in a complex context at the meso-level.

Society and Collective Behaviour

At the macro-level, design relevant frameworks and theories typically focus on interventions dealing with collective behaviour across a whole society, informing design for social change (Simon 1981; Luhmann 1995). Here, institutional factors play a dominant role in, for example, rules, regulations, policies, and informal structures, constraining or promoting collective behaviours. The main questions asked have been: Is a policy change needed instead of behavioural appeals? What incentives and regulations can be put in place and/or promoted to make certain behaviours beneficial or mandatory?

Human behaviour at this level has been extensively discussed in the fields of political science, innovation, industrial ecology, and earth systems sciences. Again, we highlight a selection of theories particularly relevant to designers, including collective behaviour in social movements (e.g. Tilly et al. 2004), diffusion of innovations theory (Rogers 1983), and the multilevel systems perspective (Geels 2002).

First, a key means of change at this scale is through engagement with social movements – collective actions towards a common goal (e.g. Tilly et al. 2004). Social movements promote legislative and policy changes to advance their causes and build coalitions with policy-makers, for example, attempting to create change (Occupy Wall Street, Arab Spring), to resist change (anti-globalisation movement), or to provide a political voice to those otherwise disenfranchised (civil rights movements). Examples of social movements range from local, e.g. grassroots innovations such as energy initiatives or local food communities, to global, e.g. the Slow Food movement, especially since modern technology has allowed us a near-constant stream of information about the quest for social change around the world (Little and McGivern 2014). Here, technology plays an increasingly important role in mobilising social change and can function as a lever for intervention from an engineering systems design perspective. For example, social media has the potential to dramatically transform how people get involved, as seen during Obama's campaign in 2008 (Little and McGivern 2014). In addition, social movements go through a number of stages in a life cycle from preliminary, coalescence, institutionalisation, to decline (Blumer 1969). Thus, by positioning with respect to social movements, their associated technologies, and life cycle, stage engineering systems can better adapt and deliver sequences of interventions.

Second, diffusion of innovations theory (Rogers 1983) addresses how, why, and at what rate new ideas, products, technologies, or social practices spread. The end result of this diffusion is that people, as part of a social system, adopt a new idea, behaviour, product, or technology. Key to adoption is that the person must perceive the idea, behaviour, or product as new or innovative. Accordingly, there are different categories of 'adopters'; hence, it is important to understand the characteristics of the target population when promoting an intervention or aiming for adoption of an innovation, e.g. technological systems (Talke and Hultink 2010). Diffusion principles can be used to explain receptivity and can also be operationalised to accelerate the rate of adoption and broaden the reach of innovations. This has been used successfully in a number of fields including agriculture, criminal justice, communication, health care (Dearing and Cox 2018), marketing, product development, and social work. However, there is evidence to suggest that such theory works better for new behaviours rather than cessation or prevention and does not take into account individuals' resources or social support (Dearing and Cox 2018). Thus, while this is an important lens for engineering system designers aiming at delivering new ideas, innovations, or behaviours, it should be used with caution and an eye towards context.

Finally, system innovation, whole systems change, and whole systems transitions (Steffen et al. 2020) are key to understanding social, technical (economic), and environmental factors in designing transitions, e.g. to sustainable futures. Here, the multilevel perspective (MLP) (e.g. (Geels 2002)) emphasises how contemporary environmental problems, such as climate change, loss of biodiversity, and resource depletion (clean water, oil, forests, fish stocks, etc.) present formidable societal challenges. Addressing these problems requires orders of magnitude more improvements in environmental performance, which can only be realised by deep, long-term structural changes in transport, energy, agri-food, and other systems (e.g. Elzen et al. 2004; Grin et al. 2010). Such changes are often called 'sociotechnical transitions', because they entail changes in technology, policy, markets, consumer practices, infrastructure, cultural meaning, and scientific knowledge (Elzen et al. 2004), and involve actors such as firms and industries, policy-makers and politicians, consumers, civil society, engineers, and researchers. Transitions are therefore complex and long-term processes comprising multiple actors (Geels 2002). Thus, system-based approaches to behaviour (change) transitions are essential.

Collectively these theories give an insight into changes in society at large, where social movements intersect with technological innovations and environmental changes, and other external factors. Thus, in this conceptualisation, consideration focuses on complex, whole systems interactions between humans and technology at the macro-level.

Reflecting and Concluding on the Human-First Perspective

In going forwards, from a human-first perspective, we see three emerging themes linking humans and technology: first, digital phenotyping, e.g. using digital twin technology (Schwartz et al. 2020) to collect behavioural data to understand and model behavioural patterns (Thorpe et al. 2019); second, interactive and dynamic personalisation of experiences – services, learning, and health treatment responses – enabled by technology (Schwartz et al. 2020); and third, an increased focus on the self, emphasising greater attention to mindsets and postures for developing as humans, for direct human social interactions, and in connection with nature (Irwin 2015).

Ultimately, we see an overall movement towards the need for an integrated approach to the human-first perspective, cutting across the relatively distinct work at each level. This has the potential to breakdown the commonly applied differentiation in literature between micro−/individual-, meso−/group, and macro−/societal levels, by characterising each as entry points for whole systems change.

Bridging and Connecting 'Technology-First' and 'Human-First' Perspectives Through Design

As we have seen in the previous sections, multiple theories, models, approaches, techniques, and taxonomies can help shed light on what influences human behaviour and behaviour change in a systemic world. Further, we also find works beginning to go towards prescription, for example, by mapping behavioural problems and behaviour change techniques (e.g. Cash et al. 2020) or defining specific steps in designing interventions (Craig et al. 2008; Davidson et al. 2020). However, these also reveal how such discussions are currently siloed by perspective, level of intervention, discipline, or application domain. Thus, in order to move forwards, it is possible to use systems design as a connecting lens, enabling insights from across the landscape to be brought together in a united overall approach.

Taking a systems design lens, the technology-first and human-first perspectives become two complementary sides of the same landscape (Fig. 1), with systems interventions cutting across both perspectives and levels: from the micro−/individual, to the meso−/group, and to the macro−/societal level. This positions design at the intersection, with interactions between levels highlighted as key to design for complex situations (Spencer and Bailey 2020), design for impact (Fokkinga et al. 2020), and design for behaviour change (Niedderer et al. 2017). However, such synthesis is not without challenges. As such, we first aim to illustrate the connected view of human and technology at each level in this section before offering guidance on how to navigate this landscape in section "Navigational Guidance for Effective Interventions".

Designing Interventions at the Micro-level

At this level, design is most often associated with affecting human behaviour by shaping interfaces, products, and services. Major design frameworks primarily taking the micro-level as starting point include human-centred design in the context of user experience (UX) and user interfaces (UI) (Norman 1988; Buxton 2007), persuasive design (e.g. Fogg 2009; Lockton et al. 2010), and (intervention) design for sustainable behaviour (e.g. Lilley 2009; Bhamra et al. 2011).

First, in terms of interaction design, user interface, and user experience (UI/UX) design (Norman 1988; Buxton 2007; Andersen and Maier 2019), six general design principles have been become widespread:

1. **Visibility**: the more visible an element, the more likely it is that people will know about it and know how to use it.
2. **Feedback**: making it clear to the user what action has been taken and accomplished.
3. **Constraints**: limiting interaction possibilities.
4. **Mapping**: establishing the relationships between controls and effect they have.
5. **Consistency**: having similar operations and similar elements for achieving similar tasks.
6. **Affordance**: providing clues that allow people to know how to use the artefact.

Together, these principles provide foundational guidance across a wide range of design contexts at this level.

Second, persuasive design focuses on influencing behaviour through a product or service's characteristics (Oinas-Kukkonen and Harjumaa 2009), for example, by integrating principles of persuasion, such as praise or reciprocation, into the use of a service to encourage a specific behaviour. While persuasive design is most widely used in e-commerce and public health (e.g. Kelders et al. 2012), it can be applied to most fields that require a target audience's long-term engagement. A highly cited framework in this context is Fogg's behavioural model (FBM), (Fogg 2009). Fogg describes behaviour change as dependent on a combination of *motivation* (linking a desired behaviour to drivers, such as pleasure/pain, hope/fear, or social acceptance/rejection), *ability* (the ease of a desired behaviour in terms of time, money, physical or mental effort, as well as the degree to which it requires change from the routine), and *triggers* (the prompts to actually take action). For behavioural design to succeed, an individual must be sufficiently motivated, have the ability, and have the right (time) trigger. In this context, the Design with Intent toolkit provides a collection of design patterns as inspirations for achieving these different outcomes (Lockton et al. 2010). Drawing on participatory design principles in its use with stakeholders, the toolkit supports the exploration of different ways of intervening in interactions. As such, persuasive design extends the basic principles of interaction design, to provide a number of concrete approaches to supporting desired behaviour in users without resorting to negative tactics such as coercion or deception.

Finally, there are a number of approaches that extend this even further, for example, towards environmentally sustainable practices as a whole (Lilley 2009; Bhamra et al. 2011). While still primarily rooted in individual behaviour, these connect human and technology by focusing on (smart) products or systems as the basis for behavioural interventions. For example, in 'ecofeedback', seeing how much water is used when washing hands or how much energy is used with different household devices allows users to understand the environmental impact of the products and services they use and thus provide aspects of motivation, ability, and potentially triggers for behaviour change (Lilley 2009; Daae and Boks 2015). One may also think of a broader understanding of ecological behaviour using the example of travel mode choice and habitual behaviour (Daae and Boks 2015). Thus, these frameworks help understand how designers can link multiple actions and their consequences when designing for behaviour change.

Generally, design at the micro-level is focused on designing for an individual and their interaction with a device or service. This provides a basis for designing specific technologies and technological interactions, where behaviour change can be somewhat isolated from the complexities of the wider sociotechnical system. Thus, these provide an essential foundation for design, as whatever the desired level of change, interventions will inevitably be manifest in a specific technology at some point.

Designing Interventions at the Meso-level

At the meso-level, design takes on a wider purview, dealing with the design of services and interactions, substantial technical systems and structures ranging from whole product lines, combinations of products and services, to buildings and organisations. Major design frameworks at the meso-level range in focus from key design steps (Wynn et al. 2019), to user involvement, co-production, and co-creation, including service design, product/service systems design, and servitisation (for overview, see Raddats et al. 2019).

First, service design (Shostack 1982) aims to improve employees' and customers' experience as a whole (Norman 1988). For example, in the case of a restaurant, service design would deal with operations and food delivery. This includes the whole life cycle of a service from, in this case, sourcing and receiving ingredients to communication between employees and customers. Each part contributes to the overall experience. Interactions between people, physical or digital artefacts, and process steps along the service journey are typically mapped using a service blueprint, as a diagram that visualises the relationships between the different parts linked to touchpoints in a journey (Clatworthy 2011). While an application, a website, or a kiosk is the 'what' that people might encounter as part of a whole end-to-end experience, service design is the 'how', focusing on how does that end experience get created. It primarily includes people, processes, and the technology that have to align in order to make all the different pieces of the users' experience. Within an organisation, we might think of multiple departments aligning to create the (customer) experience, including marketing, sales, product development, or customer Support. Thus, service design aligns different departments and silos to create a cohesive experience, which is important to directing and maintaining behaviour change.

Second, key to creating coherent user experiences (Schifferstein and Hekkert 2008) are aligned product service bundles, often termed product/service systems (PSS) (Morelli 2006). Here, users interact with a mix of products and services, for example, buying performance (hours of use) rather than the product itself, e.g. car sharing (BMW, Share Now). As such, there is a need to understand and align user experience across product(s) and service(s) in order to form coherent whole. This alignment is key to a number of major behavioural changes aimed at reducing consumption, for example, via car sharing. Unsurprisingly then, PSS models are emerging as a means to enable collaborative consumption of both products and services, with the aim of pro-environmental outcomes, sustainable PSS (Mont and Lindhqvist 2003), and business model innovation, e.g. for circular economy (Pieroni et al. 2019). For system designers, this means focusing on value to the user, experience satisfaction, and consistent behaviour across the whole product system life cycle, taking account of multiple scenarios and combinations of complex processes and data streams. It also means designing with awareness of potential systemic effects, such as rebound where, for example, a consumer may spend saved time or money in an unsustainable way, offsetting potential environmental benefits. Thus, product service design forms a logical extension of service design in shaping overall behaviour.

Generally design at this level, connects the behaviour of multiple individuals, interacting with multiple products and services over time. This provides a basis for connecting the design of specific technologies and technological interactions with wider behaviour change within a group. Thus, these provide an essential basis for linking multiple micro- and macro-level behavioural interventions into a cohesive whole.

Designing Interventions at the Macro-level

At the macro-level, design deals with large-scale, dynamic, and complex challenges, in other words, designing for society or for societal change/transformation. Here, the scope ranges from the creation of new technologies (e.g. digital health records), to the development of new forms of governance, and to whole new ways of understanding problems and/or their solutions (De Vries et al. 2016). Major design frameworks at the macro-level include directions for framing and reframing transitions into the future, social design/design for social impact and systems change, and policy design/design in the public sector.

First, building on the idea of (re)framing, Frame Innovation (e.g. Dorst 2015) and Transition Design (Irwin 2015) provide key ways to envisaging potentially different futures. Here, designers reformulate problems and take new perspectives in order to inform new solution approaches (Dorst 2015). This type of (re)framing can take place not only within an organisation but also spark change in perspective across networks of stakeholders. Examples range from designing out crime through both product and systemic changes to developing new approaches to inclusive social housing. Key to designing for human behaviour in this context is involving major stakeholders as empowered ‘designers’ coming together around a common problem. This basic approach also forms the foundation for Transition Design, which has a particular focus on creating more equitable and sustainable futures. This makes the concept of involving stakeholders in (re)framing even more explicit by arguing that fundamental change at every level of society is needed in order to address problems, such as climate change, loss of biodiversity, depletion of natural resources, and the widening gap between rich and poor (Irwin 2015: Abstract). This is based on an understanding of the interconnectedness and interdependency of social, economic, political, and natural systems. Fundamentally, then, Transition Design embodies much of what we have discussed in this chapter, highlighting the need for multidisciplinary (re)framing of problems, linking human and technical perspectives across levels over time in order to deliver effective social change.

Second, following this social lens, social design focuses on creating societal change through the broad application of design methodologies (Margolin and Margolin 2002). This builds on Papanek’s idea of creating change within the design field and no longer tolerating *misdesign*, i.e. any design that does not account for the needs of all people and disregards its own environmental consequences (Papanek 1972). Here, in particular, designers are socially and morally responsible, with responsibility for the consequences of their designs on society. This takes a whole systems view where solutions often leverage or ‘amplify’ existing, underutilised resources and designers work as facilitators and catalysts within transdisciplinary teams. Solutions benefit multiple stakeholders and empower communities to act in the public, private, commercial, and non-profit sectors. As such, this approach to design challenges existing socioeconomic and political paradigms. For example, *Designing for Society* (Tromp and Hekkert 2018) builds on these roots in order to develop a socially conscious design, where societal challenges cannot be understood without considering the complex sociotechnical systems that support our way of living. Thus, these approaches reinforce and concretise the cross cutting approach to design.

Finally, policy design/design for policy and governance/public sector service design (e.g. De Vries et al. 2016; Bailey and Lloyd 2016; Bason 2017) focuses on citizens' engagement in the co-production of civic technologies, such as open government, or user-generated public services, with the view towards transforming governments. This comes in response to calls for greater innovation at the interface between governments and their public, highlighted in recent global events such as the COVID-19 pandemic and the formulation of the United Nation's Sustainable Development Goals (United Nations 2020). Here, design for policy and governance describes the process of systematically developing effective human-centred policies based on a combination of collaborative approaches, evidence-based criteria, and novel concepts while leveraging design-driven research methods (Bailey and Lloyd 2016). For example, for questions of urban development or energy transitions, proposals for reaching large-scale stakeholder participation include ideas such as 'City Olympics' as hackathons on a city-scale (Brockmann and Helbing 2013). In this example, hackathons are conceptualised as participatory design, where diverse stakeholders, including citizens, social communities, NGOs, local businesses, cities, municipalities, and academic institutions, collectively work on urban development decisions. This is supported by new communication technologies and participatory sensing such as social computing (San Miguel et al. 2012). In this context, behavioural approaches to public policy design and policy-level interventions have become more visible in recent years, with, for example, nudging being widely used to combat the COVID-19 pandemic. However, such approaches are complex and require significant effort in addressing at least four main challenges: (i) designing for diverse contexts and contextual effects; (ii) understanding potentially diverse future scenarios; (iii) situating interventions within the systemic eco-system; and (iv) iteratively prototyping and continuing to adapt interventions over time (Schmidt and Stenger 2021). Thus, policy design brings together all the prior elements addressed in this chapter to consider whole systems change.

Generally design at this level deals with 'messy' whole systems problems. Importantly, while micro- and meso-level design approaches typically stay within existing socioeconomic and political paradigms, approaches at the macro-level begin to question such underlying premises and begin to envisage potentially different futures. Here, we also come back to our core message; to truly design for lasting social impact, designers must think systemically, uniting approaches from across levels.

Reflecting and Concluding on Designing as Connecting and Bridging Perspectives

In going forward, from a linked technical-human perspective, designing shifts its scope and nature (Subrahmanian et al. 2018), moving from a focus on products and services to interactions within complex sociotechnical engineering systems: designing for society. In other words, we observe a movement from designing for consumers (products) and users (product interaction) to designing with and for people (e.g. public goods and governmental services such as the military, police, infrastructures including public roads, bridges, tunnels, water supply, sewers, electrical grids, telecommunications, public education, or health and care services) (Sanders and Stappers 2012). This demands an increased focus on understanding and designing for human behaviour linking product, service, and systems solutions.

Ultimately, while we have shown how designing connects and bridges technical and human perspectives across levels, we notice that, to date, design approaches typically remain level-specific. This is in contrast to systems thinking, which focuses on delivering interventions that leverage diverse technical and behavioural solutions linked across levels and over time. Here, interventions trigger changes that may be incremental but can also lead to cascading effects or phase transitions (Irwin 2015), where micro-level changes can have ripple effects at the macro-level and an intervention at the macro-level will have consequences elsewhere. Thus, in the next section, we examine how to navigate in this complex landscape.

Navigational Guidance for Effective Interventions

Given the interconnection between technological and human perspectives across levels, and the increasing need for engineering systems designers to deliver coherent solutions synthesising interventions and interactions from across this landscape, four key challenges and subsequent propositions emerge from literature.

First, behavioural interventions can be delivered via diverse products, services, and systems and across levels, all of which interact and influence one another. Thus, designers face questions of where to start and how we might leverage synergies between multiple solutions at different levels in a process over time?

Second, behavioural interventions can only be evaluated if the parameters for effectiveness are clearly understood and operationalised. Intervention descriptions are incomplete when they do not describe both: which theoretical methods they use and to which practical applications these were translated. Thus, designers must deal with interventions in systems where methods and approaches come together from different and often siloed perspectives and where effects ripple across the whole landscape, taking into account interconnections between levels.

Third, behaviour change raises ethical questions regarding both whether it is right or proper to change behaviours and in what instances change is mandated and how to deal with potential unintended side effects, alternative implications, and emergent responses not originally envisaged by the designer. Thus, designers must understand how behavioural interventions take place within the context of adequate ethical considerations.

Finally, behaviour is dynamic. Critically, this means designers face diverse future scenarios where the behaviour of both systems and the humans within these can change dramatically. Thus, designers must acknowledge this potential for change and plan for how it might be monitored and adapted to or risk interventions rapidly becoming obsolete, ineffective, or even detrimental.

Considering these challenges, this section firstly describes four points of navigational guidance when designing for human behaviour in a systemic world and secondly provides examples from the domains of health, sustainability, and urban infrastructure in order to illustrate aspects of this integrative approach.

Describing an Integrative Intervention Perspective Through Theory

In this section, we distil four propositions from literature for effective intervention design in this context: to transform systems means:

1. **Levels as leverage points**: Iteratively moving between individual intervention and whole systems views in order to manage complexity and ensure alignment and cohesion in the intended behaviour (change)
2. **Interconnections between levels**: Conceptualising interventions as events in systems, and a broader idea of shaping behaviour as part of an evolving system
3. **Thinking through implications**: Working through possible consequences and engaging with possible ethical concerns during both the design process and after the launch of an intervention
4. **Adopting a temporal perspective**: Working with a reflexive, agile perspective able to monitor, reflect on, and react to a changing system over time

Levels as Leverage Points: Iteration Across Levels

The different levels at which a designer can deliver an intervention provide concrete leverage points for system change (Meadows and Wright 2008), i.e. specific places to intervene in a system where the design scope can be limited, at least temporarily. Here, designers might use interventions at each level, but in order for these to be effective, they must work in harmony. As such, the designers iteratively constrain their scope in order to limit complexity and concretise specific interventions and then broaden their view in order to examine interactions with other interventions across levels, before again constraining and iterating individual interventions. For example, according to the UNICEF, while behaviour change implies individual change, social change seeks to create an enabling environment for change, creating a strong interaction between these levels (UNICEF 2018). Importantly, this also implies a need to involve stakeholders from across levels and engage them in the development process. Thus, a designer must move between individual intervention and whole systems views in order to manage complexity and ensure alignment and cohesion in the intended behaviour change.

This is reflected in discussions surrounding complex systems, systems transitions, and the multilevel perspective (MLP) (e.g. Geels 2002). In particular, a growing literature has advocated movement towards complex systems approaches to social intervention research (e.g. (Hawe et al. 2009; Moore et al. 2019). For example, new guidance on taking account of context in population health intervention research concludes that ‘a comprehensive understanding of interventions in context implies the adoption of a systems approach’ (Craig et al. 2008: p. 26). Further, the MLP has been picked up in sustainability transition discussions. ‘Sustainability transitions refer to long-term, multi-dimensional and fundamental transformation processes through which established sociotechnical systems shift to more sustainable modes of production and consumption’ (Markard et al. 2012: p. 965). Similarly, the V-model provides a technology-focused framework for iterative alignment between developments across levels, with the designer moving between macro-level overview and micro-level development in order to ensure synergy between the overall system and its individual elements. Further examples of using this approach to align multiple concrete leverage points across levels can be found in guidance on behaviour change from the National Institute for Health and Clinical Excellence (NICE) (2007) or from the United Nations Children’s Fund (UNICEF 2018). For example, the UNICEF has used a socioecological lens to understand the interplay between individual, community (group), and societal factors affecting behaviour. Thus, while designers must limit their scope in order to deliver concrete interventions at a specific level, understanding these as connected leverage points in a wider system is essential.

Interconnections Between Levels: Interventions as Events in Systems

Following this view of leverage points affecting a common system, it becomes increasingly difficult to isolate interventions from one another. Fundamentally, the interconnections between levels mean that any intervention must be understood in its context as just one event contributing to the overall behaviour of a dynamic system. This again brings the complex systems lens to the fore (Moore et al. 2019) and means that the (dynamic) context within which an intervention occurs needs to be taken into consideration right at the outset (Moore et al. 2019). Such a position highlights the extent to which behaviour is shaped by interactions among a diverse range of ever-changing stakeholders and emphasises the contextual nature of human behaviour (Hawe et al. 2009). As such, interventions have ripple effects that potentially impact subsequent interventions. Thus, a designer in this context must look beyond specific interventions and towards a broader idea of shaping behaviour as part of an evolving system, where there is a need for iteration, reflexivity, and adaption in the design, delivery, and maintenance of interactions.

This view is reflected in discussions within, for example, the context of public health and education. Here, Hawe et al. (2009) argue that rather than viewing public health interventions as a set of de-contextualised components, they should be conceptualised as ‘events’ within complex (social) systems. Hawe et al. (2009) illustrate this with the following: ‘[S]chools, communities and worksites can be thought of as complex ecological systems. They can be theorised on three dimensions: (1) their constituent activity settings (e.g., clubs, festivals, assemblies, classrooms); (2) the social networks that connect the people and the settings; and (3) time. An intervention may then be seen as a critical event in the history of a system, leading to the evolution of new structures of interaction and new shared meanings’

(Hawe et al. 2009: p. 267). As another example, consider tobacco production and consumption. Here, Moore et al. (2019) explain how smoke-free legislation is an example of an upstream public health intervention that formed a critical event within the history of the tobacco control system. Leading up to this legislation, emerging science on harms of second-hand smoking was reframed as public discourse in a way that challenged objections phrased on the grounds of civil liberties (Moore et al. 2019). Timing matters and here the system moved towards a tipping point where the right configuration of context and mechanisms enabled the conditions for change. Legislation once opposed as authoritarian or viewed as being against liberal principles was embraced. For instance, the acceptability of smoking in front of non-smokers continued to decline, and the dominant public opinion turned towards child protection and bans on smoking in cars carrying children followed (Moore et al. 2019). This illustrates the connectedness of interventions, which together form a series of events steering changes in the dynamics of the wider system. Thus, designers must move away from conceptualising and evaluating interventions in isolation and towards understanding the value of interventions in terms of their contribution to the overall desired outcome in relation to the wider system.

Thinking Through Implications: Engaging with Ethics

When designing interventions for this dynamic systemic context, weighing up the ethical implications, potential unintended consequences, and other possible outcomes is of critical importance. This poses two key ethical questions to designers. First, when is it right or appropriate to change behaviours and in what instances is change mandated (Tengland 2012); and second, how can interventions be understood in the face of diverse ethical and equity considerations, which can vary across populations, contexts, and time. In this vein, Berdichevsky and Neuenschwander (1999: p. 52) suggest eight ethical principles that support a designer in self-reflection and culminate in the ‘golden rule’ that: ‘The creators of a persuasive technology should never seek to persuade a person or persons of something they themselves would not consent to be persuaded to do’. However, self-reflection alone is not sufficient. Ethical responsibility also means asking questions related to the wider impact of an intervention, the envisaged societal outcomes, and relevant responsibilities surrounding the intervention and its impact over time and subsequently engaging the stakeholders needed to understand these. Thus, while it is impossible to account for all possible outcomes, designers face an obligation to engage with possible ethical and equity concerns during both the design process and after the launch of an intervention (van den Hoven et al. 2015).

This is reflected in discussions surrounding how data is (transparently) used to support and define behavioural interventions. Specifically, taking COVID-19 as an example, governmental strategies have at their heart predictions about human behaviour. As Yates (2020) writes, predictions are based on analysing past patterns of human behaviour. Drawing inferences from past behaviour for future interventions can be highly uncertain and can potentially neglect key contextual factors influencing how stakeholders will perceive and engage with an intervention. Following this line of argument, policy-makers have begun to speak about behaviour development instead of behaviour change and prioritise co-creative approaches to stakeholder engagement and change. Connecting back to the examples in section "Levels as Leverage Points: Iteration Across Levels", socioecological lenses can be key to unpacking the views, needs, and concerns of varied groups. Notably, the UNICEF has successfully employed interactive, participatory strategies to ensure a holistic view of people's desires, needs, and barriers and facilitators to change. In particular, human-centred design approaches are infused into their work and ensure that people in their various stakeholder roles are a part of intervention design, formative research, prototyping, and implementation. In this way ethical considerations are foregrounded throughout the design process as well as following an intervention. Hence, a prerequisite for 'thinking through' implications is to acknowledge the inherent uncertainty of such systems and embrace engagement with stakeholders as well as the up-front need to work with ethical issues across the whole life cycle of an intervention.

Adopting a Temporal Perspective: Reflexive Agility in the Face of Complexity

In the context of rippling interventions and associated ethical issues, taking a temporal perspective to interventions is critical. However, while there are many theories and examples of designing for human behaviour feeding into intervention design, interventions across levels and their systemic effects over time defy simplification. Here, complex systems are often considered intractable. As Meadows, observes: '[D]ynamic systems studies usually are not designed to predict what will happen. Rather, they're designed to explore what would happen, if a number of driving factors unfold in a range of different ways' (Meadows and Wright 2008). While this forms a daunting barrier to design, insights from entrepreneurial and design thinking, reflexivity, and reflective practice can offer a way forwards. As succinctly put by the UK Government: 'By applying the think like a system, act like an entrepreneur mindset, we do not attempt to take on grand societal challenges in their entirety, instead we look to identify nimble opportunities for change within the system, seed innovations, test prototypes and support successful efforts to grow and influence other parts of the wider system' (Conway et al. 2017: p. 16). Thus, while designers must embrace the moral and ethical requirement to examine and plan for the potential implications of their interventions (section "Thinking Through Implications: Engaging with Ethics"), they must also accept that not all implications can be predicted and that in order to succeed they must be able to monitor, reflect on, and react to a changing system over time.

This approach is reflected in growing calls to move away from preventive interventions that focus on a combination or 'package' of activities and/or their educational messages to focus on the dynamic properties of the context into which the intervention is introduced (Hawe et al. 2009). For example, traditional behavioural economics and nudge type interventions have been criticised for their (in)ability to resiliently sustain behaviour over time across diverse contexts and populations (Hoolohan and Browne 2020). As Schmidt and Stenger (2021: Abstract) put it: '[behavioural public policy] problem-solving approaches remain optimized to achieve tactical success and are evaluated by short-term metrics with the assumption of stable systems. As a result, current methodologies may contribute to the development of solutions that appear well formed but become ‘brittle’ in the face of more complex contexts if they fail to consider important contextual cues, broader system forces, and emergent conditions’. For example, in the environmental context, such approaches demand the simultaneous adoption of multiple, substantially new, and often challenging pro-environmental behaviours on an unprecedented scale, calling into question the reality of achieving such impact via individual interventions. As such, a systemic view focuses on how and when interventions should be evaluated and how overall they could be made more effective. Hence, this is about encouraging designers to think about the harmonious orchestration of various interventions across levels and time, in other words, to work reflexively with a system in order to guide the emergence of desired behaviour over time, through many linked interventions.

Illustrating Engineering Systems Design for Behaviour Through Examples

Designing for human behaviour (change) has become a ubiquitous objective for policy-makers and other practitioners involved in trying to promote positive change in society. In this section, we explore some examples in order to illustrate our four propositions (denoted in the examples) from section “Describing an Integrative Intervention Perspective Through Theory”.

Health Behaviour: COVID-19

There is growing recognition that many challenges to improving, e.g. healthcare service provision are related to behavioural issues (Davis et al. 2015). COVID-19 serves as an example where a systemic design approach (see also Jones and Kijima 2018), focusing on designing for human behaviour, was essential to societal change, with behavioural interventions being recognised as having the potential to transform the health of populations. Here it has become apparent that human behaviour is central to transmission of SARS-Cov-2 (the virus that causes COVID-19), and changing behaviour is thus crucial to slowing transmission as well as to supporting vaccination and other longer-term solutions.

In this example, behavioural insights were embedded in national-level governance (Sanders et al. 2021), with designers and policy-makers leveraging multiple individual interventions at various levels to deliver wider behaviour change across society as a whole (*Proposition 1*). Critically, this has allowed individual interventions to be developed, implemented, evaluated, and revised, while – when successful – also aligning with the wider set of interventions at both the macro- and micro-levels. Further, as each intervention on its own only provides a small percentage of impact, the coordination of multiple interventions as a means of steering the whole system towards safer behaviour in general has been decisive (*Proposition 2*). Here, those countries that were effective to date were the ones that were able to coordinate multiple interventions across the country, instigated the interventions for adoption at appropriate points in time for the local context, and engaged in simulating multiple what-if scenarios (Haug et al. 2020). As such, aligning the periodic easing and tightening of regulations with associated interventions has proven central to effective coordination strategies (*Proposition 4*). Finally, almost all interventions involved some degree of intrusion on personal behaviour, ranging from relatively small (e.g. handwashing) to very substantial (e.g. hard lockdowns). As such, throughout the pandemic, efforts to reduce transmission of the virus have had to be weighed against social and economic cost to individuals and society (West et al. 2020: 451). When done well, this has been supported by continuous and extensive engagement between policy-makers and stakeholders from across the population (Proposition 3). This has helped to mitigate challenges and where mitigation is not possible (such as in a lockdown), make the global need more transparent from the individual perspective increasing engagement and reducing resistance. Here, such activities have been key to managing public perception at all levels as well as enabling policy-makers reflexively to change strategies over time in order to maintain the effect of interventions.

Environmentally Conscious Behaviour: Energy Use at Home

Designing for environmentally conscious behaviour has seen a number of developments in recent years, with a call to move from product thinking to a large-scale system view, i.e. thinking in terms of coordinated efforts contributing to overall (energy) transitions. In this context, and unlike the prior example, personal environmentally conscious energy use at home is more directly enacted and led by the individual.

In this example, there is a need to coordinate and leverage varied interventions across levels in order to align macro-level governance with micro-level user behaviour (*Proposition 1*). For example, on the level of the individual, smart thermostats with visually appealing and intuitive user interfaces can help direct behaviour. These individual products are then connected to other smart home appliances and introduce the potential for mutual reinforcement of environmental behaviour across, for example, thermostat, washing machine, and faucet (Moe Beitiks 2010). Further still, these link to changes in billing, regulation, and governmental incentive schemes for types of (alternative) energy sources at the macro-level. However, as many of these interventions interact with the wider sociotechnical engineering system of energy, it is necessary to directly account for such interactions in their design (*Proposition 2*). Taking the smart thermostat as example, despite being installed in millions of homes, the vast majority of users neglect to program them. As a result, users do not receive the intended benefit of scheduling heating and cooling temperatures for day and night, home and away, and so on. In response, the Nest Learning Thermostat is one of a new generation of smart home devices that automatically develops a program with comfortable set points, allowing users to easily adjust the settings and update the program (Eppinger and Maier 2019). Critical to much of the effectiveness of these interventions is that they mesh with or shape the habits and routines of the consumer and thus have the potential to reinforce wider longer-term system change when such temporal considerations are included at the design stage (*Proposition 4*). Here again, individual power for making changes is brought to the fore, as is reflexivity over time if an individual can develop good monitoring and thereby consumption practices. Notably, the benefits of such a change also support increased transparency and awareness of the impact of an intervention in the home, helping consumers to understand the impact on their own behaviour (*Proposition 3*). However, such devices also open consumers to myriad new risks (such as home-focused cyber-attack) that are, as yet, not widely understood by the public. As such, the need for ethical engagement is just as critical in this more self-directed context as in the prior health example.

Urban Behaviour: London Millennium Footbridge

Designing future cities highlights the interplay between technical and social behaviour, which interact to create emergent phenomena that need to be considered and may otherwise have unintended and undesired consequences. Here, the London Millennium Footbridge provides an example where such an interplay was central to a major engineering failure, and, as such, we discuss this more forensically than the prior examples. Specifically, technical behaviour, in the form of an increasing swaying motion, and human behavioural responses, in the form of people adjusting their steps and getting in tune with themselves and the bridge, resulted in the need to close and modify the bridge.

In this example, although the bridge had undergone tests, it turned out that the natural motion of people crossing the bridge caused minor moves in the bridge that led all walkers to adjust their stance at the same time. This created a feedback loop as the swaying motion increased and people adjusted their stance more drastically. Importantly, this translated each individual's response into something that influenced everyone else on the bridge as well as the bridge itself. This highlights how interconnections between individual and group level behaviour can have a significant impact when not considered at the design stage (*Proposition 2*). Critical to this failure was a reliance on models that focused on the technical behaviour and did not sufficiently account for interactions between individual and group behaviours. This serves to highlight how, even when a model has been tested many times, there is always the possibility that something new emerges, especially at the intersection between technical and social behaviour across levels. As such, even in apparently 'simple' contexts that have been seen many times before (designing a bridge), thinking through implications and reflexively managing human behavioural responses is key (*Proposition 3*). This also highlights the need to be aware of our underlying models about behaviour from a temporal perspective. What is a shared understanding and methodology around how models of behaviour are tested? What kind of evidence is needed to say that the model needs to be refined or extended? In this case, computer simulations were not enough. Real-life testing and redesign to account for people's behaviour was needed (*Proposition 4*). Further, the ultimate solution to the problem required redesign of the bridge (introducing dampers), which leveraged an intervention in the technical domain to impact individual level behaviour and subsequently group level behaviour (*Proposition 1*). Collectively, it resulted in a costly engineering embarrassment, not to sufficiently recognise the challenges reflected in our four propositions as well as the failure not to sufficiently recognise the fundamental engineering systems design perspective on across levels interconnected technical and human behaviour.

Conclusions

This chapter has reviewed and synthesised research on human behaviour in the context of engineering systems design. First, we describe how this literature can be understood from two main perspectives (technology-first and human-first), which are bridged by design at three main levels (micro or individual, meso or group, and macro or societal). Second, based on this conceptualisation, we provide an overview of major frameworks accounting for human behaviour and design for behaviour (change) theories and techniques (Fig. 1). They teach us about ourselves and others, and designing for human behaviour allows asking what future will we make possible. Third, we distil key challenges and corresponding navigational guidance for dealing with design in this context:

1. **Levels as leverage points**: Iteratively moving between individual intervention and whole systems views in order to manage complexity and ensure alignment and cohesion in the intended behaviour (change)
2. **Interconnections between levels**: Conceptualising interventions as events in systems and a broader idea of shaping behaviour as part of an evolving system
3. **Thinking through implications**: Working through possible consequences and engaging with possible ethical and equity considerations during both the design process and after the launch of an intervention, and
4. **Adopting a temporal perspective**: Working with a reflexive, agile perspective able to monitor, reflect on, and react to a changing system over time

Critically, these put a focus on being able to work with and coordinate many linked interventions, utilising diverse approaches, across multiple levels, over time. In turn this highlights the need for contextual, ethical sensitivity, stakeholder involvement, and interdisciplinary working.

Untimely, the overview and navigational guidance provided in this chapter provide a designer with starting points for engaging with human behaviour (change) in a systemic world. It also provides ideas of the challenges involved in this process, the inevitable need to engage with specialists from across domains, as well as those whose behaviour is intended be influenced.

In conclusion, we embrace the idea that in a complex situation, there is no one right or final solution; rather, designers must seek to guide the evolution of a dynamic system over time.

Cross-References

► Asking Effective Questions: Awareness of Bias in Designerly Thinking
► Designing for Technical Behaviour
► Digitalisation of Society
► Engineering Systems Design Goals and Stakeholder Needs
► Ethics and Equity-Centred Perspectives in Engineering Systems Design
► Evaluating Engineering Systems Interventions

► Human Behaviour, Roles, and Processes
► Public Policy and Engineering Systems Synergy

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Designing for Technical Behaviour

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Jitesh H. Panchal and Paul T. Grogan

Contents

J. H. Panchal (✉)
School of Mechanical Engineering, Purdue University, West Lafayette, IN, USA
e-mail: panchal@purdue.edu

P. T. Grogan
School of Systems and Enterprises, Stevens Institute of Technology, Hoboken, NJ, USA
e-mail: pgrogan@stevens.edu

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https://doi.org/10.1007/978-3-030-81159-4_17

Abstract

This chapter focuses on strategies for technical design of engineering systems. The strategies allow designers to manage the complexity arising from the interconnected nature of engineering systems, while achieving both technical and business objectives. The design strategies discussed in the chapter include hierarchical decomposition, modularity, design for emergent behaviors, modeling and simulation, and optimization-based strategies. Hierarchical decomposition forms the basis for traditional top-down systems engineering processes where the overall system is decomposed into quasi-independent modules which can be developed concurrently and integrated into the overall system. While decomposition-based approaches are ideally suited for achieving functional properties of the system, they do not provide guidance for achieving emergent properties. The strategies for design of emergent properties include design for quality, design for changeability, and, more generally, design for X. To support both top-down functional design and design for emergent properties, commonly used modeling and simulation approaches, and optimization-based approaches are discussed. The chapter discusses challenges and trade-offs in designing complex engineering systems for technical behavior, such as complexity vs. robustness, requirements vs. value, modularity vs. performance, and the interactions between social and technical aspects.

Keywords

Emergent behavior · Engineering systems · Engineering systems design · Hierarchy · Modeling and simulation · Modularity

Introduction

Systems such as aircraft, cars, and power plants are complex technical systems that operate in the context of complex socio-technical environments of air transportation system, ground transportation system, and energy infrastructure, respectively. The design of the technical aspects of these engineered systems itself is highly challenging because of their scale and complexity (Bloebaum and McGowan 2012), let alone the consideration of interacting social and technical aspects which are considered in other chapters. The systems are complex in the sense that there are physical interactions between different subsystems that need to be managed to design a system that achieves the desired functionality. A single engineer or a team of engineers cannot have the complete knowledge required to develop them, necessitating the use of a large number of individuals with diverse expertise. Their design and development typically involve hundreds to thousands of individuals working across organizational boundaries and frequently across different countries.

Systems design for technical behavior has been studied in application-specific domains such as aerospace, automotive, and software engineering and by diverse scientific communities in systems science, optimization, control, etc. Collectively, research and development has resulted in methods, processes, principles, heuristics, and models for systems design. Many books and journals are devoted to the topic. Given the breadth of the topic, it is not possible to cover it in a single book, let alone a single chapter. Therefore, the goal of this chapter is to present some of the fundamental ideas and approaches that form the basis of design for technical behavior. These include (i) hierarchical decomposition-based approaches for achieving functional requirements of the system; (ii) approaches for design for emergent system properties such as quality, reliability, and changeability; (iii) modeling and simulation for systems analysis; and (iv) optimization-based approaches for systems design.

The chapter is organized as follows. In section "Hierarchical Decomposition-Based Strategies," we discuss hierarchical decomposition-based approaches on which traditional top-down systems engineering processes are based. The basic ideas in these techniques consider systems to be nearly decomposable (Simon 1991, 1996), decoupling complex systems into quasi-independent modules, improving those somewhat independently, and then recombining or reconfiguring them to larger technical systems. Hierarchical decomposition has many advantages for systems design, including increased concurrency and reduced complexity of systems development activities. However, decomposition-based processes are not suitable for achieving emergent properties, which arise from the interactions between parts of a system, and require a holistic view of the system and its lifecycle. We discuss approaches for addressing such systems-level emergent properties in section "Design for Emergent System Properties."

Modeling and simulation are playing an increasing crucial role in systems design, particularly design for technical behavior. Section "Modeling and Simulation for Systems Analysis" is focused on modeling and simulation approaches which can be used when the technical knowledge of the systems can be reduced to mathematical equations or encapsulated into simulation models. In section "Optimization-Based Approaches for Systems Design," we discuss optimization-based approaches that have been successfully used in automotive and aerospace systems design and are being applied to other application domains.

Systems design is driven by multiple objectives related to the technical performance, emergent properties, the efficiency with which design is carried out, and longer-term objectives of changeability and evolvability. Several challenges and trade-offs in technical systems design are discussed in section "Challenges in Designing for Technical Behavior." Finally, a summary is presented in section "Summary."

Hierarchical Decomposition-Based Strategies

In his classic paper titled "Architecture of Complexity," Simon (1991) argued that many natural complex systems have a nearly decomposable, hierarchic structure, which allows them to evolve. A wide variety of systems, ranging from physical and biological systems to social systems, exhibit hierarchies where, at each level in the hierarchy, the system can be partitioned into modules such that the interactions *within* the modules are significantly stronger than the interactions *among* the modules. Simon (1991) also argued that near decomposability is essential for comprehensibility. Humans have difficulty understanding systems that are complex but not hierarchical. Due to the limited cognitive and computational capabilities, it is difficult to account for all the interactions between different components of the systems. Comprehensibility is essential for designing technical systems. Without a deep understanding of system behavior, and the interactions between different components, it is impossible to design complex engineered systems.

Modularity and hierarchy are the core principles in the technical design of systems. The principles are used throughout the technical processes of systems engineering. For example, the requirement definition process consists of hierarchical decomposition of the top-level technical requirements to the subsystem-level and component-level requirements. This enables design activities to be carried out independently and, in parallel, across different modular subsystems by domain-specific experts. The technical interactions among the modular subsystems are managed during the design process through communication, and the potential effects of the interactions are tested during the integration, verification, and validation processes. The details of modularity and hierarchical decomposition are discussed in sections "Modularity" and "Hierarchical Decomposition," respectively. The embodiment of these principles in systems engineering processes is presented in section "Use of Modularity and Hierarchical Decomposition in Systems Engineering Processes."

Modularity

Modularity is a way of managing complexity by dividing a system into smaller components and designing the components independently (Baldwin and Clark 2002). A modular system is composed of quasi-independent parts that are tightly integrated within themselves. The interactions among the modules can be abstracted into simple interfaces that hide the complexity and information within the modules.

One of the best examples of a modular technical system is computer hardware, which is clearly decomposed into modular components with clearly defined standardized interfaces. Modularity is also a key feature of object-oriented programming. The interfaces define the flow of information between the different modules while hiding the internal functions of the modules. Engineered systems such as automobiles, aircraft, and spacecraft are all built with varying levels of modularity.

Advantages of Modularity

There are many advantages of modularity in engineering systems design. One of the primary advantages of modular systems design is that it reduces coordination costs. Design tasks across modules are independent of each other and, therefore, can be carried out by different teams working independently. A modular system reduces the amount of information exchange needed between stakeholders, enabling concurrent development processes, and reducing dependencies among teams and across organizational boundaries. Modularity also enables outsourcing and specialization of firms. Due to clear interfaces between subsystems, clear performance-based contracts can be established for subsystem development.

Modularity reduces production costs (Paralikas et al. 2011) by increasing reusability and standardization of parts across different systems. It simplifies production processes, and the production of modular systems can leverage economies of scale. Modularity reduces the cost of managing diverse parts and enables customization of systems for the needs of different users. It provides the flexibility for customers to tailor the products based on their preferences. Modularity accommodates uncertainty and enhances the evolvability of systems. Modular systems are more robust and resilient to exogenous changes. In response to external changes, the design of individual modules/subsystems can be improved independently of the changes in other modules.

Modularity of Product and System Architectures

The principle of modularity can be used to characterize different types of product and system architectures. Ulrich (1995) defines a product architecture as a "the scheme by which the function of a product is allocated to physical components." Within systems engineering, the architecture of a system is defined as "the fundamental concepts or properties of a system in its environment embodied in its elements, relationships, and in the principles of its design and evolution" (Walden et al. 2015).

A product architecture consists of three parts: (i) the arrangement of the functional elements, (ii) the mapping from functional elements to physical elements (i.e., the parts, components, and sub-assemblies), and (iii) the specification of the interfaces among interacting physical embodiments of the different functions. Ulrich defines two major classes of product architectures: integral and modular. In an *integral architecture*, the components are highly coupled with each other, and there is a lack of clear set of mappings from functions to physical realizations. Therefore, changes in a component result in significant changes to other components. In contrast to integral architectures, a *modular architecture* has a one-to-one mapping between the functions and components (Ulrich 1995). Modular architectures are further categorized into slot, bus, and sectional architectures. The slot architecture represents a one-to-one mapping from functions to physical realizations. The bus architecture has a common component called a bus to which the other physical components connect via the same types of interfaces.

Measuring Modularity

The general idea is that the greater the decoupling between modules, the greater the modularity. There have been many attempts at measuring modularity (Hölttä-Otto and de Weck 2007; Guo and Gershenson 2004; Sosa et al. 2007). The product architecture is typically represented as a network with modules as nodes in the network and the interdependencies as the links. The network can also be mapped to a matrix representation called the design structure matrix (DSM), further discussed in section "Matrix-Based Modeling Methods."

Modularity can be quantified using graph-theoretic measures. For example, Sosa et al. (2007) define component modularity as the level of independence of a component from the other components within a product. They present three measures of component modularity based on the construct of network centrality. *Degree modularity* is based on the idea that modularity is inversely proportional to the number of components that affect (or are affected by) the design of the component. *Distance modularity* is based on the idea that the modularity of component depends on how distant (in a network sense) it is from all other components in the product. *Bridge modularity* is based on the number of times a component appears in the path between two other components.

Hierarchical Decomposition

Hierarchical decomposition goes hand in hand with the principle of modularity for managing complexity. Within product design, the overall function of the product is hierarchically decomposed into sub-functions, which are satisfied by sub-assemblies and components. Similarly, systems engineering processes heavily leverage requirement hierarchies and product-breakdown structures. These product hierarchies can be mapped to organizational hierarchies and can greatly help in managing the complexity of systems engineering and design.

Consider the example of an automotive system hierarchy. The eight major systems and the corresponding subsystems in an automotive product include (Bhise 2017, pp. 12–13) the following:

1. *Body system*: body-in-white, closures system, seat system, instrument panel, exterior lamps, glass system, rear vision system
2. *Chassis system*: underbody framework, suspension system, steering system, braking system, wheels and tires
3. *Powertrain system*: engine, transmission, shafts and joints, final drive and axle
4. *Fuel system*: fuel tank, fuel lines
5. *Electrical system*: battery, alternator, wiring harness, power controls
6. *Climate control system*: heater, air conditioner, climate controls
7. *Safety and security system*: air bag system, seat belt system, wiping and defroster system, driver assistant systems
8. *Driver interface and infotainment system*: primary and secondary vehicle controls and displays, audio system, navigation system, CD/DVD system

The top-level requirements for a pickup truck are typically specified in terms of the towing capacity, the payload, off road capability, fuel economy, access, and safety. These requirements are cascaded down to lower-level entities in the system hierarchy. For example, the safety requirement of the vehicle cascades down to the braking system (e.g., stop vehicle within a specified distance), which then cascades down to the hydraulic subsystem (e.g., delivering specified brake fluid pressure under max load) and the mechanical system (e.g., brake pads designed to meet stopping distance requirements) (Bhise 2017).

Similarly, space systems are typically decomposed into the following subsystems: propulsion, attitude control system, position and orbit determination and control system, command and data handling system, telemetry, tracking and command system, power system, thermal control system, and structures and mechanisms (Wertz and Larson 1999).

The development of a requirement hierarchy entails systematically mapping the top-level mission objectives into a complete set of verifiable technical requirements. The requirement hierarchy includes requirements about the functional needs (i.e., what functions need to be performed), performance requirements (i.e., how well the functions need to be performed), and interface requirements. The functional and performance requirements are allocated across the system to sub-functions, objects, people, or processes. The decomposition and allocation process continues hierarchically until a complete set of design-to requirements is achieved (NASA 2016).

Hierarchical decomposition helps in determining a clear information flow and alignment between product structure and organizational structure. Requirements flow from top to down in the hierarchy, and design solutions are synthesized and validated from the bottom to the top in the hierarchy. Clear hierarchical decomposition enables requirement traceability and facilitates verification and validation.

Use of Modularity and Hierarchical Decomposition in Systems Engineering Processes

The principles of modularity and hierarchical decomposition are embedded in the systems engineering Vee model (Forsberg and Mooz 1992; Walden et al. 2015) and the technical processes in systems engineering (see Table 1). The systems engineering Vee, shown in Fig. 1, is a commonly adopted model for systems design. The horizontal axis represents time, and the vertical axis represents abstraction. The left side of the Vee represents the activities for system definition. It consists of requirements decomposition and design. The right side of the Vee represents system integration and testing.

The Vee model is implemented within organizations through a number of systems engineering processes. INCOSE (Walden et al. 2015) classifies SE lifecycle processes into four types: technical processes, technical management processes, agreement processes, and organizational project-enabling processes. The *technical processes* are used to define verifiable requirements, to develop system architectures,

Table 1 Technical processes in systems engineering and their purpose (ISO/IEC/IEEE 15288)

Technical process	Purpose
Business or mission analysis process	To define the business or mission problem or opportunity, characterize the solution space, and determine the potential solution class(es) that could address a problem or take advantage of an opportunity
Stakeholder needs and requirement definition process	To define the stakeholder requirements for a system that can provide the capabilities needed by users and other stakeholders in a defined environment
System requirement definition process	To transform the stakeholder, user-oriented view of desired capabilities into a technical view of a solution that meets the operational needs of the user
Architecture definition process	To generate system architecture alternatives, to select one of more alternative(s) that frame stakeholder concerns and meet system requirements, and to express this in a set of consistent views
Design definition process	To provide sufficient detailed data and information about the system and its elements to enable the implementation consistent with architectural entities as defined in models and views of the system architecture
System analysis process	To provide a rigorous basis for data and information for technical understanding to aid decision-making across the life cycle
Implementation process	To realize a specified system element
Integration process	To synthesize a set of system elements into a realized system (product or service) that satisfies system requirements, architecture, and design
Verification process	To provide objective evidence that a system or system element fulfills its specified requirements and characteristics
Transition process	To establish a capability for a system to provide services specified by stakeholder requirements in the operational environment
Validation process	To provide objective evidence that the system, when in use, fulfills its business or mission objectives and stakeholder requirements, achieving its intended use in its intended operational environment
Operation process	To use the system to deliver its services
Maintenance process	To sustain the capability of the system to provide a service
Disposal process	To end the existence of a system element or system for a specified intended use, to appropriately handle replaced or retired elements, and to properly attend to identified critical disposal needs

and to transform the requirements into the product. The technical processes, listed in Table 1, include business or mission analysis process, stakeholder needs and requirement definition process, architecture definition process, design definition process, system analysis process, implementation process, integration process, verification process, transition process, validation process, operation process, maintenance process, and disposal process.

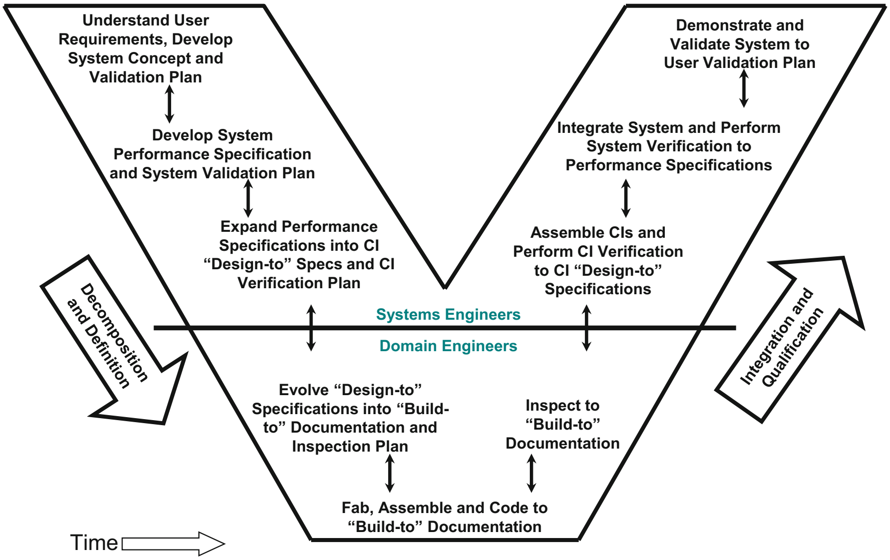

Fig. 1 The "Vee" model of systems engineering. (Adapted from Forsberg and Mooz 1992)

The requirement-based systems engineering processes focus on properties directly related to the primary function of the engineered system. For example, an aircraft systems engineering process defines a system-level mass requirement (itself derived from other performance requirements) and allocates a mass breakdown to each subsystem to constrain lower-level design activities. Rather than representing a true physical constraint on lower-level activities, the requirement flow-down is a coordination mechanism to allow design teams to parallelize work while satisfying the system-level mass. Changes to lower-level requirements can be negotiated provided that consistency of all system-level properties can be preserved, a process facilitated by maintaining traceability between system-level properties and requirement flow-downs. Design for emergent properties requires a different set of strategies, discussed in the following section.

Design for Emergent System Properties

Complex system design recognizes that not all desired properties can be designed from a hierarchical decomposition-based design process. Emergent behaviors arise from the interaction of a system and its environment and cannot be identified through traditional functional decomposition (Johnson 2006). In other words, emergence describes properties – either desirable or undesirable – that are unexpected or exhibit barriers to anticipation. Philosophically, emergence manifests in varying degrees of strength ranging from weak forms where macro-level behaviors can be generated based on knowledge of micro-level behaviors to strong forms where even complete micro-level knowledge is insufficient to explain macro-level behavior.

Emergence in the design of engineering systems arises from the large-scale, complex, and dynamic nature of the problem. These conditions reflect the limited cognitive abilities of the human designers to anticipate emergent system behaviors either due to fractured and distributed knowledge across a large or interdisciplinary design team or through limited extant knowledge of a novel or cognitively challenging problem. In general, human designers rely on design tools to encapsulate and share knowledge and automate application of knowledge to better anticipate emergent properties. In particular, simulation models discussed in greater detail in section "Modeling and Simulation for Systems Analysis" are a natural method to aggregate micro-level behaviors to macro-level behaviors.

Rather than introducing specific modeling methods to achieve desirable emergent properties or avoid undesirable ones, this section instead discusses general classes of emergent properties encountered in engineering systems design and the associated design methodologies developed to address them.

Emergence in Engineering Systems

Nearly every system-level attribute in engineering systems can be described as emergent but with widely varying strengths. For example, the total mass of an aircraft is difficult to anticipate early in a design process due to numerous disciplinary interdependencies; however, it is ultimately a simple summation of subsystem component masses. Other functional properties such as maximum climb rate depend more strongly on contributions from propulsion, aerodynamics, control surfaces, structures, etc. but could still be reasonably be deduced in a dynamic physics-based simulation with sufficient micro-level knowledge. In contrast, the overall aircraft safety cannot easily be decomposed to individual components, even though various safety elements such as redundant components, flight control software, and operating procedures are designed to achieve specific macro-level purposes.

Nonfunctional requirements are of particular interest when discussing emergence because they are different from core system functions and emphasize a distinction from traditional functional properties tied to system requirements (Glinz 2007). Engineering design literature adopted the term "ilities" to refer to a range of desirable nonfunctional properties including quality, reliability, safety, flexibility, robustness, durability, scalability, adaptability, usability, interoperability, sustainability, maintainability, testability, modularity, resilience, and others (de Weck et al. 2011). Of course, there also exist undesirable "ilities" – fragility, rigidness, expensiveness, and vulnerability – as emergent properties to be avoided.

To focus discussion on general principles for engineering systems, the remainder of this section looks at three classes of ilities as examples of designing for emergent properties. Design for quality represents the most mature literature, including traditional topics such as reliability engineering and Taguchi techniques but also newer process improvement approaches like Six Sigma. Design for changeability focuses on maintaining quality in response to disturbances through flexibility, adaptability, and robustness. Finally, design for X (DFX) encompasses several product life cycle-related qualities such as manufacturability, interoperability, and affordability.

Design for Quality

Among the most mature of ilities, design for quality pursues a product or process that generates utility for customers while establishing reliability of those functions. The term "quality" goes beyond system functions to evaluate the holistic benefit realized by customers or end users. Methods such as quality function deployment (QFD) seek to model and organize customer needs to inform technical requirements (Chan and Wu 2002). Design for quality includes planning to create products or services that meet quality objectives, operations to monitor and control quality objectives during production or delivery, and improvement processes to change the product or service to strengthen quality goals over time (Juran 1986). Design for quality intersects with related literature on reliability, robustness, and resilience.

Two main areas of quality planning in design literature include robust design methods and reliability engineering. Robust design methods pursue reduction in wasted effort through statistical understanding of variation, generally building on the work of Taguchi (Phadke 1995; Ross 1988). So-called Taguchi methods assign a loss function to quality attributes to quantitatively measure and manage cost impacts of their variation. Careful experimental design following orthogonal arrays helps to evaluate alternatives and determine the optimal set of control parameters.

Reliability engineering formulates a probabilistic system model and applies statistical analysis techniques to evaluate and optimize performance (Elsayed 2012). Reliability itself is a quality metric defined as the probability of a successful action at a given time. Modeling techniques such as reliability block diagrams or fault tree diagrams model and diagnose potential failure modes in a system. Reliability engineering generally relies on redundancy to improve system performance but can also consider other factors such as maintenance and repair.

Resilience engineering is a closely related concept that emphasizes the ability to withstand disturbances (Francis and Bekera 2014). Compared to reliability, resilience is a more dynamic quality metric that measures both the loss of performance from a disturbance but also the timeliness of recovery and whether the system can return to its original state. Resilience-based design methods rely on dynamic simulation to model system behavior in response to a disturbance.

During operations, statistical quality control methods also take a statistical approach to monitoring processes to infer when corrective action is required, in light of natural variation (Montgomery 2009). Statistical quality control is most frequently applied in manufacturing settings to monitor component tolerances or testing failure rates. The traditional analysis method uses a statistical control chart to visualize quality objectives over time to evaluate whether a process is within or out of control.

Six Sigma is the most widely recognized quality improvement approach building on early advances in total quality management (TQM) (Tennant 2001). The name arises from the goal to control a process such that quality attributes six standard deviations from the mean remain within control limits. Six Sigma methods build on robust design and quality control to improve products and services following a structured process to define, measure, analyze, design/improve, and verify/control.

Although most of the above examples allude to manufacturing settings, design for quality for software remains a distinct topic area. Software quality engineering leverages different statistical models and methods to account for logical, rather than physical, laws governing defects (Kan 2002). Advances in formal methods pursue ways to evaluate the correctness of software a priori or even enable correct-by-construction design methods that guarantee quality (Woodcock et al. 2009).

Design for Changeability

Advances in robust design and quality engineering contributed to broader interest to design systems to retain value in response to a broader set of disturbances and changes. This topic recognizes an essential trade-off between efficiency and robustness where fine-tuned optimization for one context may not be well-suited for others. Subsequent advances defined and characterized several types of changeability that facilitate dynamic responses to events. Friske and Schulz (2005) define key principles to enable changeability to include simplicity, independence, modularity, and extended principles of integrability, autonomy, scalability, non-hierarchical integration, decentralization, and redundancy.

Flexibility is one of the earliest forms of changeability studied to permit alternative system configurations in response to dynamic events. Real options use an analogy of a financial option to provide the right, but not the obligation, to execute a design change at a future time after uncertainty resolves (de Neufville 2003). Associated analysis building on financial methods such as discounted net present value and value at risk combined with decision trees and other dynamic programming methods help to define optimal control policies for when to execute real options. From this perspective, a flexible design includes a multi-state decision process to respond to uncertainty as it resolves.

More generally, Ross et al. (2008) define changeability through change mechanisms, executed by change agents, which transition a system from an initial to a final state. Change agents external to a system contribute to flexibility while those internal to a system contribute to adaptability. The effect of a change can exhibit robustness to maintain constant performance, scalability to change the level of performance, and modifiability to change the type of performance. Extensions of this perspective naturally lead to self-organizing, adaptive, or evolutionary behavior characteristic of intelligent systems where continuous feedback reinforces design and decision-making processes. Design for evolvability recognizes products, and product platforms must change to adapt to new conditions.

Design for X

Design for a broader set of lifecycle objectives such as manufacturability, assembly, affordability, and sustainability coalesce into design for X (DFX) (Kuo et al. 2001), also referred to by some as design for excellence. These objectives seek to improve design solutions by reducing direct or indirect costs that are difficult to anticipate in advance, reinforcing the knowledge-limited feedback process characteristic of designing for emergent properties. DFX broadly seeks to inform upstream design decisions using downstream lifecycle information which inherently requires a combination of expertise and modeling activities to overcome temporal causality.

Initial DFX efforts focused on production activities such as manufacturability (DFM) and assembly (DFA), recognizing that design engineers typically lack deep experience of machinists and assemblers. DFM methods emphasize the importance of material selection, geometry, and tolerances. DFA methods consider additional human factors such as ease of assembly (e.g., number of parts, fastener types, symmetry), handling and physical access, and supporting equipment. DFM and DFA benefit from frequent prototyping efforts to identify and correct issues early.

More recent DFX efforts focus on sustainability-oriented topics such as disassembly, recyclability, the environment. These long-term lifecycle objectives recognize an expanding system boundary for engineering design activities that reach beyond the initial design and manufacturing organization to a broader network of lifecycle actors. Design for sustainability seeks to reduce the undesired effects of products that typically represent only indirect costs to the original manufacturer. Additional challenges at the larger system boundary address interfaces between organizations and institutions, cultural differences, and governmental policies.

In general, DFX methods benefit from integrative design activities to address a problem from multiple perspectives and solicit broad participation of stakeholders. For example, concurrent engineering methods facilitate parallel activity and information exchange across disciplines and are well-suited for DFX methods (Huang 1996). Five pillars of concurrent engineering include the team (people), tools (software), model (design representation), process (activity sequence), and facility (infrastructure) (Knoll et al. 2018). Other DFX-enabling design methods and activities that emphasize social connections across differing stakeholder or expertise groups as a part of the design process include participatory or co-design, gaming simulation, and collaborative design.

Modeling and Simulation for Systems Analysis

Designing for technical behavior requires a creative ability to synthesize new design concepts and a predictive ability to anticipate how a proposed design achieves desired system behavior. Historically, predictive ability comes from a deep knowledge base accumulated over a long career; however, unfamiliar or novel design activities require the knowledge base to be established during design. From a cybernetic perspective, models facilitate "sensing" of system behaviors and provide information feedback for "actuating" design changes (Maier et al. 2014). In other words, models are a design tool to inform design decisions and help designers achieve desired outcomes, especially when complete knowledge is not known in advance.

A model is a simplified representation of a source system of interest within a limiting context (an experimental frame) that facilitates purposeful action – in this chapter, design. Model effectiveness is measured by its ability to improve design decisions, rather than provide an accurate representation of a system (although the two are often correlated). For example:

- A low-cost prototype allows a designer to evaluate usability of a product without committing large manufacturing expenses.
- A mathematical model allows a designer to analytically solve for design parameters to optimize for a desired behavior.
- A model contained within an information system allows a designer to distribute effort across a large engineering team and integrate individual contributions.

Furthermore, simulation models are a type of model that generates synthetic data to inform design decision-making. Stochastic simulation models the effect of random variables while dynamic simulation models the effect of time propagation.

Progress in model-based systems engineering (MBSE) highlights the central role of models in modern systems design processes where knowledge is distributed among a large design team (Ramos et al. 2012). Standardized modeling frameworks such as the systems modeling language (SysML) and object-process methodology (OPM) allow large teams of designers to share models throughout the system lifecycle via a central repository. Models define requirements, explain system concepts, decompose system functions, specify detailed designs, manage interfaces, and document verification and test plans. For example, an aircraft system model may include a computational fluid dynamics (CFD) simulation to evaluate aerodynamic properties and, based on behaviors from other subsystems such as propulsion and controls, evaluate flight dynamics requirements set at the systems level. A systems modeling environment facilitates knowledge transfer between disciplines (e.g., aerodynamics, propulsion, and controls) to achieve desired technical behavior.

Theory of Modeling and Simulation

Zeigler et al. (2000, Chap. 1–2) introduces the theory of modeling from a systems science perspective. In this literature, a model provides a logical mapping between inputs (external actions) and outputs (observable behavior) mediated by a model state (internal system structure) illustrated in Fig. 2. Three fundamental systems problems allow model users to (1) *analyze* behavior based on an assumed system structure, (2) *infer* system structure based on observed behavior, and (3) *synthesize* alternative system structures to achieve desired behavior. This chapter deals exclusively with the third type of systems problem: synthesis, better known as design.

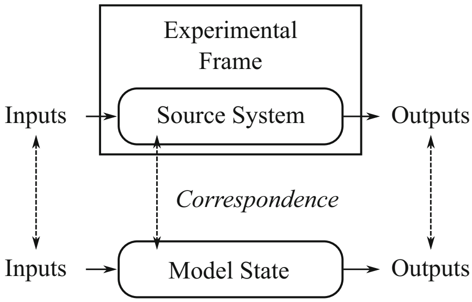

Fig. 2 A model provides a logical mapping between inputs and outputs in correspondence with those observed from a source system for a specified experimental frame

Transferring information obtained in a modeling environment back to a source system relies on a mathematical relationship called a morphism that establishes correspondence between inputs and outputs in the two settings. Defining an appropriate experimental frame determines which inputs and outputs are relevant to represent in the source system and what level of precision or fidelity is required for design objectives. Model validation assesses whether the model and source system outputs (within the reference frame of interest) agree within an acceptable error tolerance.

Several types of models may be appropriate to address a design problem depending on which characteristics the experimental frame emphasizes. This section provides an overview of the following modeling techniques:

- *Structural models*: describe the internal system structure
- *Static models*: describe how the system structure affects output behavior from an aggregated or time-invariant perspective
- *Stochastic simulations*: model how uncertainty affects output behavior
- *Dynamic simulations*: model how time affects output behavior

Several techniques build on each other. For example, dynamic simulations may incorporate stochastic features or static analysis of stochastic and dynamic models assessing output behavior for alternative system structures. The objective of modeling efforts is to acquire information about technical behaviors prior to costly and time-consuming integration and testing activities.

All four classes of modeling methods appear in design methods discussed in this chapter. Table 2 provides a rough mapping between the methods for design of technical behaviors and the associated modeling methods most frequently used.

Structural Models

Structural models define system components and their interrelationships as a conceptual device or technique for architecting, communication, or documentation. Architectural design principles such as modularity prescribe changes to system

Table 2 Rough mapping between design methods and modeling methods

Design method	Modeling method structural static stochastic dynamic			
Modularity and decomposition	x			
Design for quality		x	x	x
Design for changeability			x	x
Design for X	x	x	x	x
Optimization and tradespace exploration		x	x	

structure to achieve desired properties such as resilience and robustness. Other design methods such as model-based engineering use structural models to communicate requirements or interfaces across organizational boundaries.

Matrix-Based Modeling Methods

Matrix-based modeling methods represent a source system as a network (or graph) and encode its structure in matrix form. Matrix-based methods provide a compact mathematical notation suitable for architectural and systems-level analysis.

The most widely used matrix-based model pioneered by Steward (1981) is the *design structure matrix* (DSM) (Browning 2001; Eppinger and Browning 2012), also known in software engineering as an N-squared diagram. A DSM is a square $N \times N$ adjacency matrix that represents dependency among N components

$$\begin{bmatrix} m_{11} & \dots & m_{1N} \\ \vdots & \ddots & \vdots \\ m_{N1} & \dots & m_{NN} \end{bmatrix} \tag{1}$$

where element m_{ij} represents the relationship between component i and component j. In a design context, components can come from the product, organization, or process domains. Multi-domain matrices (MDMs) provide mappings between components in more than one domain (Bartolomei et al. 2012).

The simplest DSMs use binary elements $m_{ij} \in \{0, 1\}$ to denote existence of relationships between components; however, other forms assign scalar numbers or vector quantities to denote the strength of a relationship or multidimensional nature across physical, electrical, and logical domains. Some conventions specify m_{ij} to mean component i depending on component j while others use the converse. Some applications, such as physical connectivity, assume undirected dependencies where $m_{ij} = m_{ji}$, yielding a symmetric matrix about the diagonal. Other applications, such as logical connectivity, assume directed dependencies.

Changing the ordering of DSM rows and columns can help understand and anticipate system behaviors arising from the underlying system structure. Partitioning algorithms sequence rows and columns to cluster tightly coupled components. Modular design principles, for example, seek to minimize dependencies across modules.

Project management variations on DSMs can also predict sequential iteration arising from component dependencies (Smith and Eppinger 1997). In this method, matrix elements m_{ij} denote the probability that a change in component i propagates to require a change in component j. Changes to the task sequence (analogous to partitioning a DSM) or changes to the underlying system architecture can reduce the number of design iterations required to converge on a design.

Aside from DSM, axiomatic design theory also defines a *design matrix* as mapping between design parameters and functional requirements (Suh 1998). For an ideal product design with N design parameters $\mathbf{x} = [x_1, \ldots, x_N]$ and N functional requirements $\mathbf{y} = [y_1, \ldots, y_N]$, design matrix element $a_{i\,j}$ captures the sensitivity of functional requirement i to design parameter j, i.e., $a_{i\,j} \approx \partial y_i / \partial x_j$. A diagonal design matrix indicates uncoupled design where each design decision can be made independently. A triangular design matrix indicates decoupled design where a sequence of decisions resolves dependencies. Any other design matrix indicates a coupled design which violates desired properties in the Independence Axiom

Graphical Modeling Languages

Several types of graphical modeling languages provide expressive capabilities to describe and communicate system structure across organizational boundaries. Three most widely used languages in engineering design include the integrated computer aided manufacturing (ICAM) definition for functional modeling (IDEF0), object-process methodology (OPM), and systems modeling language (SysML). All three modeling languages originated from the field of software engineering as techniques to document and describe object-oriented information systems.

IDEF0 belongs to the IDEF family of modeling languages and focuses on function modeling (NIST 1993). It specifies a syntax and semantics for graphical diagrams that represent system functions and functional relationships.

OPM is a conceptual modeling language that distinguishes between two primitives: objects and processes (Dori 2016). Objects are entities that preserve information over time, and processes are functions that transform them.

SysML and its progenitor, unified modeling language (UML), is a general-purpose modeling language to describe systems from multiple perspectives (Friedenthal et al. 2012). SysML defines nine types of diagrams in four “pillars”: structure, behavior, requirements, and parametrics. Structural diagrams define system components and attributes. Behavioral diagrams define interactions between components, state transitions, and activities or functions. Requirement diagrams define objectives and constraints subject to engineering design. Parametric diagrams define logical or mathematical relationships between component inputs and output behavior.

Interest in digital or model-based engineering activities emphasizes the role of graphical modeling languages for two reasons. First, model-based design environments allow engineers to develop and refine a design concept before committing any resources to physical manifestation. Second, digital design environments provide a common information system that is suitable to share and distribute design effort across a large design team. Design team members can gain broader visibility of requirements flow-down, interface specifications and can more rapidly share updates or changes across design boundaries.

Static Models

Static models formulate a fixed design problem that maps input design parameters to the outputs associated with technical behavior. Although described as static, the nested model may incorporate endogenous stochastic or dynamic features which have been abstracted through methods described in the following sections. A static model presents a simple input-output interface amenable to design methods including optimization and tradespace analysis.

Analytical models are one type of static models that provide a series of computable equations that map or mathematically transform inputs to outputs. For example, a cost estimating relationship (CER) is a technique to estimate cost using a mathematical equation parameterized by system attributes, i.e., design parameters. CERs can be developed by collecting and analyzing historical data using methods such as multiple regression or simply based on expert knowledge of cost drivers.

Stochastic Simulation

Stochastic simulations generate synthetic data with uncertainty or natural variation modeled as random input variables illustrated in Fig. 3. The key components of a stochastic simulation model include the probability distribution for input random variables $f(x)$, the internal model state function $q(x)$, and the observable output function $y(q)$ which manifests as a derived random variable.

Subsequent output analysis follows two classes of methods depending on the nature of uncertainty (de Weck et al. 2007).Well-characterized uncertainty based on historical data enable concrete design guidance using statistical principles. Profound or poorly understood uncertainty over long timescales or incorporating multi-actor decisions demands alternative assessment using techniques such as game theory or scenario analysis.

Statistical Uncertainty Quantification

Uncertainty quantification generates and analyzes large numbers of simulation samples to infer technical behavior using statistical techniques such as expectation, likelihood, and belief. Two modes of uncertainty quantification address endogenous sources of epistemic uncertainty within the system designer's control and exogenous sources of aleatory variability outside the system designer's control.

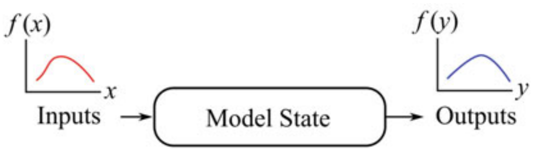

Fig. 3 Stochastic simulation maps a probability distribution of inputs $f(x)$ to a distribution of outputs $f(y)$ through an intermediate system state expression $q(x)$

Epistemic uncertainty arises from imperfect correspondence between a model and its reference system where precise values of some model parameters or properties are unknown. Uncertainty quantification methods are structured processes to understand the relationship between assumed parameter values and technical behavior. Forward methods systematically vary input parameters to understand the sign and magnitude of effects on outcome variables using statistical expectation and variance. Inverse methods use evidence from observations to select model parameters to maximize Bayesian likelihood or Dempster–Shafer belief functions.

Other sources of uncertainty arise from aleatory (natural) variation in underlying processes or the environment which can be modeled as random variables with associated probability distributions. Complex, nonlinear combinations of multiple random variables (as in system models) require Monte Carlo methods to numerically estimate the expected value or approximate the distribution of technical behaviors.

Statistical methods rely on large numbers of random samples which can be computationally prohibitive for complex system models (Giunta et al. 2006). Latin hypercube, orthogonal arrays, stratified, or importance sampling methods can reduce the number of required samples to achieve desired results. Alternatively, response surface methods such as kriging and multivariate adaptive regression splines can approximate the system model but also introduce new sources of error.

Strategic Analysis

Profound uncertainty over long timescales or among multiple actors may not be suitable to model with probability distributions required for statistical analysis. A different class of strategic analysis techniques including game theory and scenario planning rely on quantitative or qualitative assessment of a small set of alternatives.

Game theory models interactive decision-making among sets of strategic actors (Vincent 1983). Statistical analysis of outcomes is insufficient because the behavior of each actor depends on the anticipated behavior of others. Various game settings include simultaneous or sequential decisions, one-shot or repeated decisions, partial or complete information, and with (cooperative) or without (non-cooperative) communication. Alternative solution methods such as equilibrium conditions or Pareto efficiency evaluate decision strategies under interactive effects.

Scenario planning techniques structure decision-making activities for alternative futures (Go and Carroll 2004). Although there are many variations, it generally defines a small set of plausible scenarios with corresponding actors, background information, goals and objectives, and sequences of actions and events to serve as narrative for design problems. Similar to robust engineering design, viable alternatives should accommodate multiple scenarios.

Dynamic Simulation

Dynamic simulation generates synthetic time series data based on time-varying inputs and state transitions shown in Fig. 4. The key parts of a dynamic simulation model include the initial state $q(0)$, the input trajectory $x(t)$, the internal state

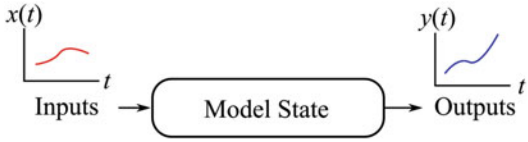

Fig. 4 Dynamic simulation maps an input trajectory $x(t)$ to an output trajectory $y(t)$ through a series of model state transitions $q(t + \Delta t) = \delta(q, x)$

transition rule $\delta(q, x) = q(t + \Delta t)$, and the observable output function $\lambda(q, x) = y(t)$. Dynamic simulation also exhibits stochastic features if any input variable takes on random values.

Dynamic simulation includes three modes of time advancement. Discrete time simulation assigns a fixed time step $\Delta t = 1$. Continuous time simulation (including system dynamics) allows positive real-valued Δt where smaller values typically achieve more accurate results. Finally, discrete event simulation varies the time step duration to efficiently process temporal events.

Dynamic simulation is frequently combined with analysis techniques such as discounted cash flow analysis, network flow, and dynamic programming to evaluate alternative decisions on two scales. Open-loop analysis uses output trajectories to evaluate the dynamic (lifecycle) properties resulting from static design decisions. Closed-loop analysis uses output trajectories as feedback to evaluate the control of operational decision policies to achieve desired technical behavior.

Static Design Analysis (Open-Loop)

State and output trajectories generated by dynamic simulations model the technical behavior of a proposed system. Aggregated information about the performance over a simulated lifecycle supports an open-loop evaluation process to select the best design alternative as a static decision. Various simulation models include finite state automata, cellular automata, discrete event simulation, system dynamics, and agent-based simulation. Although widely varying, methods can be described on a continuum between two extremes with top-down and bottom-up approaches.

The top-down approach organizes all state variables and transition rules in a common system-level structure with global information visibility. Typical examples include finite state automata, discrete event simulation, and system dynamics models. A top-down approach is best suited for monolithic or centrally controlled engineered systems with well-understood rules for system-level behavior.

The bottom-up approach defines two levels of analysis: state variables and transitions at a micro-level and emergent population-level behavior at a macro-level. Typical examples include cellular automata and agent-based models. A bottom-up approach is best suited for decentralized or distributed engineered systems with poorly understood rules for system-level behavior but well-understood rules at a lower level.

Regardless of the model approach, dynamic simulation for static design analysis aggregates temporal information for initial decision-making. For example, discounted cash flow analysis aggregates future financial value outputs (FV) at each time period t to a single measure of net present value

$$NPV = \sum_{t=1}^{N} \frac{FV(t)}{(1+r)^t} \tag{2}$$

based on a discount rate r that denotes the time value of financial resources. Other temporal analysis methods use alternative key performance measures to quantify temporal system behavior specific to each design problem.

Control Policy Analysis (Closed-Loop)

Some design applications include operational decision-making or control within the system boundary. In this setting, a dynamic simulation can maintain state information and process control actions (state transitions) to inform and evaluate alternative control policies. Design of control policies aims to find the conditional sequence of actions (policy) that optimizes an objective function.

Deterministic control problems assume perfect knowledge of the system state over an action horizon. For example, a flow network problem evaluates actions to route resources through conduits (edges) between source (origin) and sink (destination) entities (nodes). Optimal resource routing minimizes costs or maximizes volume. Based on an initial state of source node supply, sink node demand, and edge availability with defined capacity and cost, dynamic flow network problems can be formulated as a time-expanded network and solved using optimization techniques such as linear programming. A dynamic simulation may formulate and solve a flow network problem repeatedly to model a dynamic resource routing control policy.

Stochastic control problems incorporate partial information or random variables in the action horizon. In this case, methods such as dynamic programming solve a multi-stage decision problem by recursively splitting it into smaller sub-problems that can be easily solved. Real options, for example, use dynamic programming to identify optimal control policies for when to execute a flexible design option to maximize expected value (de Neufville 2003). Dynamic programming is an important element of other stochastic control problems such as Markov decision processes which models the system state and state transitions as a Markov chain. Other extensions that incorporate adaptable control policies include partially-observable Markov decision processes and reinforcement learning.

Optimization-Based Approaches for Systems Design

The simulation models of the technical behavior of systems, discussed in the previous section, relate the design choices to the functional and nonfunctional system performance. They can be used in conjunction with optimization techniques to aid systems designers in rapidly exploring the design space. Optimization is used at multiple levels within technical design processes. At the lower level of the system hierarchy, optimization can be used for component sizing (design definition process in Table 1), whereas at the higher level it can be used to select optimal system architectures (architecture definition process in Table 1). In this section, we discuss the role of optimization in technical design, and popular approaches include multi-disciplinary design optimization (MDO), meta-modeling, and multi-attribute tradespace analysis.

Role of Optimization in Engineering Systems Design

Optimization-based approaches to engineering systems design rely on the view that systems engineering is a process of maximizing value. According to Papalambros and Wilde (2000), optimization is a philosophical and tactical approach during the design process. It is a pervasive viewpoint, as opposed to being a phase in the design process.

The optimization-based view is also related to decision-based view of design. According to the decision-making view of design, designers are decision makers whose role is to make decisions. The decisions are driven by the maximization of some utility or value. Using the utility or value functions as the objective to be maximized, design decisions can be formulated as optimization problems subject to various technical and budgetary constraints. This pervasive view of decision-making and optimization in systems engineering and design is well-captured by the description by Lee and Paredis (2014), who argue that designers are value maximizers, and systems engineering and design can be viewed from the perspective of decisions that can be formulated from three increasingly comprehensive perspectives: artifact-focused perspective, process-focused perspective, and organization-focused perspective.

Multidisciplinary Design Optimization (MDO)

While it may be possible to formulate these decisions as sequential decisions, solving these optimization problems is highly challenging. Therefore, the focus is on developing ways to partition the problems along disciplinary boundaries and to coordinate the information flow between these optimization problems. Such a decomposition strategy is leveraged in the multidisciplinary design and optimization (MDO) literature.

Multidisciplinary design and optimization (MDO) (Martins and Lambe 2013) applies optimization techniques to multidisciplinary design. It is assumed that the sub-system level analysis models are available. Various formulations ranging from all-in-one optimization problem to concurrent subspace optimization have been developed. The MDP techniques can be classified based on the MDO architecture, which is a combination of optimization formulation with an organizational strategy. MDO architectures can be monolithic or distributed. Monolithic architectures cast the problem as a single optimization problem, whereas distributed architectures decompose the problem into multiple optimization problems. Examples of monolithic architectures include all-in-one formulation, simultaneous analysis and design

(SAND), individual discipline feasible (IDF), and multidisciplinary feasible (MDF). Examples of distributed architectures include concurrent subspace optimization (CSSO), collaborative optimization (CO), bilevel integrated system synthesis (BLISS), and analytical target cascading (ATC). A thorough review of MDO architectures is presented by Martins and Lambe (2013).

The optimization-based view of design also leverages the principles of hierarchical decomposition and modularity. For example, analytical target cascading (ATC) combines design optimization with requirement cascading (Kim et al. 2003). In ATC, the systems design problem is formulated as a multilevel optimization problem, where the top-level system requirements are systematically propagated down to appropriate subsystem-level specifications. The lower-level specifications are then used to perform design tasks concurrently.

Various other optimization-based formulations have been used for systems design. Examples include (i) robust design, where the objective is a combination of maximization of performance and minimization of the performance variation, and (ii) reliability-based design optimization (RBDO), where the focus is on achieving a minimum level of reliability. Other extensions of design optimizations include consideration of market-related aspects in addition to the technical aspects. For example, design for market systems formulates the design optimization problem in conjunction with game theoretic models to simulate market competition (Michalek et al. 2005).

Strategies for Design Space Exploration

Optimization-based approaches can become challenging to use for systems design if the simulation models are computationally complex. To address this challenge, strategies based on using surrogate models in design optimization have been developed during the past few decades. Surrogate models are simplified models of more complex simulation models that are developed specifically for use with optimization algorithms. Surrogate modeling approaches range from simple polynomial response surface models to advanced iterative refinement techniques that can handle the complexities associated with design problems. An example is the variable complexity response surface modeling method, which builds progressively accurate response surface models as the design space is reduced along the design process. Sequential approaches for sampling and development of meta-models, such as trust region approaches, have also been developed (Viana et al. 2014).

Approaches such as optimal learning, Bayesian global optimization (BGO), and value-based global optimization (VGO) use the value of information (VoI) to explicitly model the cost of running different models (Moore et al. 2014). The metrics not only helps the designers in choosing the next design point to sample at but also aids in deciding which model to use. Therefore, the approach combines both the artifact-related objectives and process-related objectives in decision-making.

Another strategy used for technical system design is multi-attribute tradespace analysis (Ross et al. 2004), which is a systematic approach for early-stage design that combines decision theory with tradespace analysis. The approach helps in accounting for preferences of multiple stakeholders, improves communication, and allows the stakeholders to interact concurrently. The process enables the evaluation of the impact of stakeholders' decisions on the overall systems cost and performance.

Challenges in Designing for Technical Behaviour

Technical design is a balancing act between multiple, often conflicting, objectives. The strategies of modularity and hierarchical decomposition help to reduce design complexity and increase parallelism (see section "Advantages of Modularity"). However, they come at a cost of reduced performance and efficiency. Technical design processes based on hierarchical decomposition, such as requirements engineering, have been attributed to cost and schedule overruns in complex design projects (Collopy and Hollingsworth 2011). Further, these decomposition-based approaches do not address the emergent properties of the system, as discussed in section "Design for Emergent System Properties." In this section, we explore some of the trade-offs and challenges associated with the technical design strategies discussed in this chapter.

Complexity and Robustness

Reducing complexity results in improved maintainability and lower costs, whereas increasing robustness reduces the chances of failures from external disturbances. Low complexity and high robustness are two of the important design goals for systems design. However, these two goals are interdependent in nature. It is well accepted that increasing complexity reduces robustness, but the relationship is more nuanced. Carlson and Doyle (2002) argue that designing for robustness through redundancy and feedback drives internal complexity. Complex systems such as airplanes can be designed to be much simpler with many fewer components and with the same functionality, but a simpler system would be less robust to component variations, failures, or external fluctuations. Therefore, there is an advantage of increasing system complexity. However, increasing the complexity for improving robustness to expected failures also has its downsides – the potential fragility to rare or unanticipated disturbances and the possibility of cascading failures.

Requirements and Value

Traditional systems engineering processes rely on requirements-based processes to set and control design objectives. Hierarchical decomposition of top-level system requirements into derived requirements defines technical behavior required of individual subsystems and components. At the component level, design activities aim to meet requirements at minimum cost. However, from an optimization perspective, requirements-based design presents a rigid framework where design objectives are converted into constraints that are enforced at every level of the hierarchy.

Alternative value-driven design methods build on economic foundations of decision theory to frame design decisions as maximizing system utility rather than meeting requirements at minimum cost (Collopy and Hollingsworth 2011). A value-driven framework defines a scalar value function as a holistic measure of preference for design alternatives which can be combined with multidisciplinary design optimization to achieve better trades between component-level decisions.

Although value-driven methods can be theoretically proven to be more efficient than requirements-based methods, there are practical challenges in implementing them in system design processes. It is challenging to define a value function that encompasses all desired and anticipated system behavior in a scalar quantity yet can be disaggregated to dissect the value implication of individual component-level decisions. Imperfect knowledge of the capabilities of the stakeholders and difficulties in determining their true value functions make it challenging to develop value function hierarchies that maximize the overall system's value.

Modularity and Performance

Modularity of systems provides a wide range of business benefits. Modularity enables high product variety at a lower cost and is essential for developing product families. Modularity increases commonality across products, thereby reducing production and inventory costs. Modularity makes it easier to change the design as a result of changing customer requirements. Modularity also increases the ease of service and maintainability.

While modularity improves business objectives, it also comes with a price in terms of reduced technical performance (Hölttä-Otto et al. 2005). For example, more modular systems are likely to be larger, heavier, and less efficient than their integral counterparts. Modular architectures typically have greater number of parts. Technical objectives such as light weight, compactness, and low power consumption can drive the designs away from modular architectures toward more integral architectures. The trade-off between modularity and technical performance needs careful consideration by the designers to balance the business and technical objectives.

Design models quantify and pursue desirable lifecycle properties such as modularity, flexibility, and interoperability. However, achieving these nonfunctional properties requires either higher upfront costs or reduced initial capabilities. Despite analysis techniques such as discounted cash flow analysis, executing trades between upfront costs and downstream value remains a challenging area.

Interactions Among Technically Designed Systems

Engineered systems typically operate in an environment consisting of other systems. In some scenarios, systems are independently designed and operated, but the overall performance of the larger system of independently designed system is heavily dependent on the performance of individual systems and the interactions between them. Consider the example of the overall energy infrastructure. It consists of independently designed, managed, and operated energy production and distribution systems. However, the performance of the overall system, e.g., stability, robustness, and demand response, depends on the interactions between individual systems. Other examples include the transportation infrastructure, which consists of independently designed and operated automobiles, roads, railroads, etc. These are all systems of systems (SoS), whose overall technical design cannot be carried out solely by using the approaches discussed in this chapter.

One of the primary concerns in designing SoS is that the system should be able to evolve and still achieve the overall objectives when old systems are updated, new systems are added, and systems are removed from the SoS. Traditional design issues of optimality and minimization of cost are typically not the concerns of the SoS designers. Therefore, the design of SoS requires a different set of design principles. Maier (1998) lists four examples of architecture design principles for SoS, which include (i) stable intermediate forms, (ii) policy of triage, (iii) leverage at the interfaces, and (iv) ensuring cooperation. The first principles of stable intermediate forms indicate that the constituent systems should be capable of operating on their own before the overall SoS is fully deployed. The SoS should retain technical, economic, and political stability. The triage principle implies the need to carefully select parts of the system to control. The principle of leverage at the interfaces highlights that architecting SoS is essentially designing the interfaces between systems. Within the bounds of the specified interfaces, the individual systems can be designed and operated independently. The fourth principle of ensuring collaboration guides the SoS designs toward architectures and schemes that promote collaboration between entities. Since the publication of Maier (1998), these principles for design have been expanded by the SoS community. Interested readers are referred to Jamshidi (2009) and Cantot (2011).

Interactions of Technical Behaviour with Social Aspects

The design for technical performance is also influenced by social and organizational aspects. The performance of many systems is dependent on interactions with human decision makers. For example, the performance of the energy system depends on the peak load, which in turn depends on the consumers' energy usage behavior. In such systems, the technical performance can be influenced by modifying the human behavior through policy design (e.g., through incentives or taxes).

Another example of interaction between technical design and social behavior can be seen during the design process itself (Piccolo et al. 2018). The organization that designs a technical system is a social system, whose design influences the technical design. Therefore, the system being designed, along with the organization, can be viewed as a socio-technical system. The interdependence between the organization and technical design is explored in the literature on mirroring hypothesis. According to the mirroring hypothesis, the social (communication) links within an organization (team) tend to mirror the technical dependencies in the system (Colfer 2016). The alignment of organizational structures with the structure of the system is an effective way to ensure that the technical dependencies are associated with communication channels within the organization. The coordination achieved through such an alignment of organizational structures and system architecture is referred to as socio-technical coordination. The technical design also influences the organizational aspects. For example, modularity reduces transaction costs within organizations (Baldwin 2007). These relationships between technical factors and social and organizational factors are discussed further in later chapters in the book.

Summary

The chapter discussed strategies for addressing the challenges associated with designing complex engineering systems for technical behavior. The strategies include modularity, hierarchical decomposition, optimization-based approaches, and design for emergent behaviors. The strategies are embodied in contemporary systems engineering processes and methods. Various modeling and simulation techniques supplement these strategies. Structural models help in modeling the entities within systems and their interrelationships. Static models map the relationships between the input design parameters and the outputs related to technical behavior. Stochastic and dynamic models capture the uncertainties in the systems and the time varying aspects of the systems, respectively. Systems design is inherently multi-objective in nature, with multiple objectives that pull the design in different directions. Striking a balance between competing objectives such as complexity, robustness, modularity, and performance is an essential aspect of designing for technical performance. Finally, the technical design of a complex engineering system in the context of other systems and broader social and organizational aspects requires unique considerations, which are explored further in the following chapters.

Cross-References

- ▶ Architecting Engineering Systems: Designing Critical Interfaces
- ▶ Design Perspectives, Theories, and Processes for Engineering Systems Design
- ▶ Designing for Human Behaviour in a Systemic World
- ▶ Dynamics and Emergence: Case Examples from Literature
- ▶ Engineering Systems in Flux: Designing and Evaluating Interventions in Dynamic Systems
- ▶ Engineering Systems Integration, Testing, and Validation
- ▶ Evaluating Engineering Systems Interventions
- ▶ Flexibility and Real Options in Engineering Systems Design
- ▶ Formulating Engineering Systems Requirements
- ▶ Properties of Engineering Systems

▶ Research Methods for Supporting Engineering Systems Design
▶ Technical and Social Complexity
▶ The Evolution of Complex Engineering Systems
▶ Transitioning to Sustainable Engineering Systems

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Dynamics and Emergence: Case Examples from Literature

18

Mo Mansouri and Mario Štorga

Contents

M. Mansouri (✉)
School of Systems and Enterprises, Stevens Institute of Technology, Hoboken, NJ, USA

Department of Science and Industry Systems, University of South-Eastern Norway, Kongsberg, Norway
e-mail: mo.mansouri@stevens.edu

M. Štorga
Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Zagreb, Croatia

Department of Business Administration, Technology and Social Sciences, Luleå University of Technology, Luleå, Sweden
e-mail: mario.storga@fsb.hr

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Abstract

The concept of emergence has roots in systems complexity and dynamics, with prominent impact in contemporary science and in design, analysis, and governance of complex engineering systems. It is almost impossible to effectively model emergence within the dynamics of systems, due to the obscurity of its nature and imperfection of our information on its relational systemic interactions. Thus, paying attention to basic meta-questions about emergent properties of complex engineering systems is crucially important in understanding both the trajectories of evolution of systems and correspondingly the patterns of system behaviour. From this trajectorial/behavioural perspective, emergence and dynamics are considered as very close concepts: understanding the variables of one can be realised by tracing and modelling the other. This chapter reviews and summarises the topics of emergence and dynamics through their applications in six case examples. Six studies conducted by researchers around the world are selected, representing a portfolio of cases studied with multiple theoretical foundations, levels of scope, application domains of engineering systems design, phenomena of emergence, and modelling methods used that detect and identify emergence through dynamics. The case reviews provide a gateway to comprehending emergence in systems through emphasising the dynamics of interactions.

Keywords

Case studies · Complex systems · Dynamic behaviour · Emergence · Engineering systems · Modelling and simulation · Resilience

Introduction

The interconnectedness among a myriad of active nodes in systems creates transaction-based complex networks. These interactions fuel the non-linearity of outcomes. The agency of nodes leads to eminence of systems patterns and properties, collectively. This is an inevitable complexity of any large-scale engineered or socio-technical system, where the agency of components is given. Some behavioural patterns are predictable and known as a function of the designed governing dynamics. However, some other outcomes are known but unpredictable and categorised as emergence (Mansouri and Mostashari 2010).

There are complexities caused by countless and often nested interactions among diversified and ever-changing actors within the boundary of an engineered or self-organising system. Such complexities are brought by an uncontrollable dynamic that challenges the governability of systems from an endogenous perspective (Darabi et al. 2012). Nevertheless, systems governance and intra-network management processes are responsible for understanding such dynamics and developing effective mechanisms to influence them towards the desired outcomes. An effective governing framework is used to decipher unpredictable emergence through mechanisms and policies.

In cases in which the agency of actors is given, governing the emergence is most effective when defined by consensus among all acting stakeholders. To reach such consensus, it is imperative to gather all theoretical conceptions that establish the scope, domain, typology, and methodology by which such dynamics is generated; hence, emergent properties originate. These conceptions and variables define systemic properties that are the primary source for the behavioural outcome of the system. Governing consensus are often reached through acknowledgement and adoption of systemic properties by all the internal agents and other stakeholders of the system at large.

This chapter focuses on summarising conclusions that are the result of a governing consensus among stakeholders in complex systems. This is done through investigating the results of several case studies in the realm of systems modelling. These cases are representative of problem-solving methodologies, dedicated to understanding systems emergence and dynamics. Our intention is to detect and extract a meta-narrative for combining theory and applications of complexity as well as cognitive and behavioural approaches used for designing engineering systems selected in this chapter.

An approach founded on the wisdom of experts in the field is essential beyond the confinement of each case for all engineering system thinkers: to better understand the sources of dynamic interactions, explore how they create emergent properties, and study how their governing structure evolves, while striving for effectiveness and efficiency as well as resilience and continuity over time. To do so, we need to adopt qualitative insights from theories of design, complexity, organisational behaviour, or systems thinking and enrich them with describing applications of quantitative techniques such as agent-based modelling, system dynamics modelling, social network analysis, and game theory.

We start the chapter by defining the terms in the form of a brief literature overview. This will provide necessary guidelines to identify the relationship between dynamics within a complex engineering system and emergence that emanates over time, particularly in the selected cases. We will continue by introducing the tools and techniques used for capturing evolution over time in complex systems. Causal loop analysis and control systems will be reviewed concerning understating the dynamics of systems.

We will also discuss the possibilities of influencing such dynamics to pursue positive emergent properties through mechanism design, based on systems governance and management principles. This, as mentioned previously, might be a guideline for enabling system designers to plan a higher likelihood of occurrence for specific emergent outcomes. This can be done through leveraging forces of interactions within the system. Such levers shed light on emergent properties and how they might come to existence as a result of dynamics, be it caused by internal or external agents in the system.

Following the section dedicated to the literature review on the topics of interest and introducing a foundation for theoretical development, we present the applications of emergence and dynamics in practice through reviewing multiple case studies. A series of cases are selected methodically for this purpose to include a portfolio of perspectives and approaches in practice for solving various problems in different domains, yet within a similar context of engineering systems. In other words, as for the methods of selection, the variety of domains studied in the cases and the differences in their adopted methodologies along with many other factors, including their relevance to the topics of our interest, are the reasons for our selection.

Rather than focusing on the technicality of the modelling approaches, the model, or its results in detail, special attention is instead paid to the capacity of each model that is covered in the case for predicting, documenting, or explaining the systems' emergence based on its dynamics. The adaptability and scalability of approaches has also been considered as an important factor for choosing these cases. There will be a brief explanation of the logic for each selection in the same section in which the cases are presented. The bigger picture will be also captured in tabular format for creating a more effective readers' connection map.

Finally, the last part of the chapter covers the concluding remarks collected from previous sections. The purpose of this section is to connect the dots and illustrate a clearer picture of the necessary steps that should be taken for understanding dynamics in engineered systems and their emergent properties through modelling and other qualitative or quantitative methods, cases of which are presented throughout the entire chapter. The conversation will also be taken to describe how other concepts such as systems governance, self-organisation, and resilience are related to the emergence and dynamics of complex systems.

Definitions and Contextual Background

Emergence has a Latin root compounding two words *e-* and *merge*, meaning *out* and *dip*, respectively. This suggests the rise of a hidden object out of unforeseen circumstances (Wildman and Shults 2018). However, from a design and engineering perspective, the idea is to realise the hidden aspects of such emergent properties as they manifest themselves. This will have to be done based on existing patterns of trajectory in similar cases. That is why emergence has a different meaning when it comes to the design and engineering of systems.

An *engineered system* is defined as "a system designed or adapted to interact with an anticipated operational environment to achieve one or more intended purposes while complying with applicable constraints" (INCOSE n.d.). Most complex systems, however, evolved over time and under the pressure of many endogenous and exogenous forces. The agency of the system components has an impact on the level of the system's overall complexity.

The *dynamics of interactions* become more complicated when purposeful agents are competing and collaborating over the resources. This naturally results in competing games initially, but as time goes by, it gets elevated to game-changing and even paradigm-shifting activities. The consequences of such interactions are not always known, nor can they be predictable (Nikolic and Kasmire 2013). This brings us to the realm of emergent properties, the world of unknowns that is captured under the term of emergence.

There are existing methodologies that have been applied for understanding the dynamics of systems. Some of the well-known ones include techniques such as Petri Nets, Cellular Automata, Discrete Event, Markov Chain, System Dynamics, and Agent-Based Modelling. However, an exhaustive list is difficult to provide since the line between these approaches is not strictly defined (Balestrini Robinson 2009) and many models utilise aspects of several techniques. Nevertheless, Balestrini Robinson argues that Network Simulations and Analysis, System Dynamics, and Agent-Based Modelling techniques can satisfy the widest span of modelling needs. These thoughts are considered computational and are most applicable to cases in which no closed-form solution may be found.

Network Simulation and Analysis represents a system of interest in the form of a network, that is, a graph where vertices represent entities and relationships between entities are represented by edges. Relationships can have different weights, can be directed, or can be of various types. Erdös and Rényi (Erdős and Rényi 1959) first used networks to represent and study complex systems, laying the groundwork for numerous later applications. Network Simulation is often used to simulate communication networks, social proximity, or exchange of data packages over the Internet.

System Dynamics is a perspective and set of conceptual tools that enable us to understand the structure and dynamics of complex systems (Sterman 2000). System Dynamics is also a rigorous modelling method that allows us to build formal computer simulations and to design more effective complex engineering systems.

Engineering System Dynamics is a modelling method for analysing complex engineered systems characterised by feedback loops and time delays (Ottino 2004). It is a holistic approach in that it gives us a view of the primary interactions and their feedback effects that drive the functioning of the entire system. It is used in many areas, from trying to model ecosystems to economies and large engineering projects.

Agent-Based Modelling and Simulation is another quantitative approach in which a collection of autonomous acting entities called agents are modelled to interact and make decisions. Since each agent individually assesses its situation and takes action based on a set of rules, which are called rules of the game, the trajectory of collective behaviour may delineate emergent properties of the system (Bonabeau 2002). Repetitive games such as competition, collaboration, and coordination will be the commonly known interactions among agents, which rely on the computational capacity to explore dynamics of interactions and possibly emergent properties of collective action instead of findings of mathematical models.

Emergence describes a process whereby parts interact to form different forms of synergies. These synergies then add value to the combined organisation, which gives rise to the emergence of a new macro-level of an organisation that is a product of the synergies between the parts and not simply the properties of these parts themselves (Goldstein 2011). In the science of complexity, the predominant "conceptual guide" to emergence is the concept of *self-organisation* as it has been interpreted according to three interrelated bases, described in the following. The term "self-organisation" has become so intertwined with the term "emergence" that today they are often used synonymously.

The first basis comes from an amalgam of constructs and methods developed in both the far-from-equilibrium platform created by the Nobel Laureate Ilya Prigogine (Glansdorff and Prigogine 1971) and the closely related framework developed in the research programme of synergetic established by the German physicist Hermann Haken (Haken 2011). The second basis comes out of the cybernetics approach going back to around the time of WWII. This basis of self-organisation has incorporated elements of information theory, control and guided systems, an inquiry into homeostasis, and related themes. The third basis is that heritage of the idea of self-organisation understood as circularly causal, adaptive self-regulation in biological organisms, a framework going back two centuries to the idealist, Romanticist orientations of Immanuel Kant, Friedrich Wilhelm Joseph Schelling (Johnson 2006), and other *Naturphilosophers*. Most of the complexity research and theorising concerning emergence relies on some combination of these three bases.

Emergent properties of a system are those which emerge out of its complexity. One claim is that 'emergent properties' represent one of the most significant challenges for engineering complex systems (Johnson 2006). They can be thought of as unexpected behaviours that stem from the interaction between the components of an application and their environment. In some contexts, emergent properties can be beneficial; users adapt products to support tasks that designers never intended. They can also be harmful if they undermine important safety requirements.

There is, however, considerable disagreement about the nature of 'emergent properties'. Some include almost any unexpected properties exhibited by a complex system. Others refer to emergent properties when an application exhibits behaviour that cannot be identified through functional decomposition. In other words, the system is more than the sum of its parts.

Understanding these concepts can also provide us with insights about *governing complex systems* through systems thinking approaches or, as Meadows liked to refer to it through, 'thinking in systems' (Meadows 2008). Complex engineering systems produce nonlinear behaviour because of the emergent properties of the myriad of interactions among its agents. This makes them challenging to understand and analyse even from a modelling perspective. That is why modelling approaches such as system dynamics capture the effect of delay to predict and document the emergence of "tipping points" (Gladwell 2002) as well as trigger mechanisms that cause system state changes towards a different trajectory over time (Scheffer 2009). This is why the governance and management strategies that worked in the past may not be effective in the future; hence a different governance framework must be developed.

Self-organisation too is considered one of the characteristics of complex systems. This characteristic might be present in three types of circumstances. The first type is in the ability of diversified agents to engage in joint collaborative actions in pursuit of a shared vision. The second type involves the achievement and sustainment of an equilibrium, which results from many decisions made by actors based on their own utility while pursuing coordination of systems' stability. The third type includes the idea of resilience, which is the capacity of a system to absorb and adapt to disruptions, internally resulting from autonomous agents within the system and without experiencing any change of state (Young 2017).

Ultimately, resilience as a property of complex systems in action is considered definitive of emergent behaviours that it manifests. Consequently, that is why self-organisation and emergence are reflecting on agency of subsystems or actors within the boundaries of the system under study and hence referring to the same phenomenon; a thought that we will revisit later on in this chapter.

Selection and Review of Cases from Literature

There is vast literature on the topic of emergence. Parts of it belong to philosophy within the sections of metaphysics and philosophy of science, where the focus is on the concept of completeness and fundamentality. Completeness indicates the challenges of knowledge in both systems and their agents; in a most generic sense due to this intrinsic lack of perfection. Fundamentality is related to stakeholders and their perspectives and refers to the topic from a phenomenological lens. Other research on emergence is captured in computational sciences and engineering. These are particularly emphasising its impact on language and linguistic blocks in programming as well as emergent failures in software development.

There is also a myriad of topics within the context of basic sciences such as physics, chemistry, biology, agriculture, management, and operations research as well as newly emerging sub-sections and interdisciplinary sciences, such as cell- and molecular biology, microbiology, epidemiology, neuroscience, genetic herding, and complexity theories to name some that include concepts of emergence or emergent properties in their research. Recognition that understanding emergent behaviour requires a focus on the emergent collective properties that characterise the system as a whole and a search for their origin made emergence the unifying paradigm in contemporary science. It means identifying emergent collective patterns and regularities through experiment or observation and then devising models that embody candidate collective organising concepts and principles that might explain them. These patterns, principles, and models are the gateways to understand emergent behaviour observed in the complex systems that are under study in different disciplines.

The illustration of the above claims is derived from analytics provided within the Web of Science toolkit for the analysis of the literature published on emergence-related topics. Figure 1 depicts an overview of the number of publications in each research area for the key phrase 'emergence in complex engineering systems', recognised within the topics of the publications in the period 1950–2020. Figures 2 and 3 also represent the number of publications based on the categorisation of sources and their clustering based on the research groups in different universities and educational or research centres.

However, the focus of this chapter is on the research done within the specific field of engineering systems, design, systems sciences, networks, complexities, and behavioural sciences, where they are applied to resilience and governance. In this chapters' review, applications are of particular interest, to complement theoretical aspects of emergence and dynamics covered elsewhere in the Handbook. That is why we have considered a selective series of cases as the basis of the literature review and focused on those case studies directly connected to the topics of engineering systems design. A series of applications spanning different systems

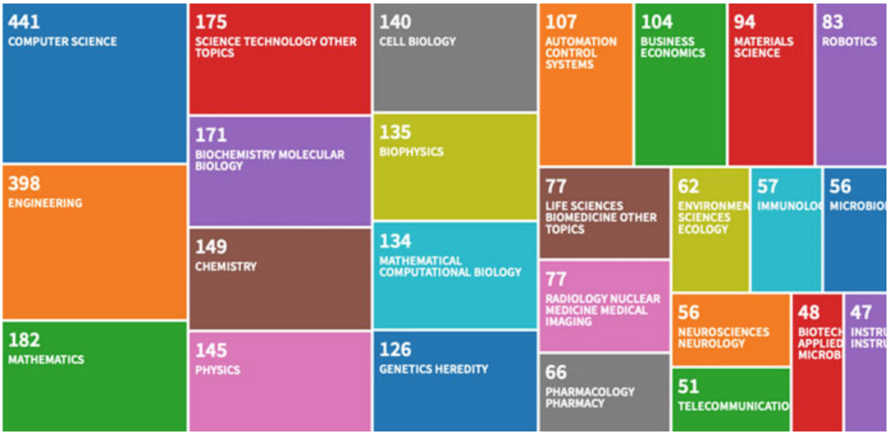

Fig. 1 An overview on the number of publications categorised by the research area (from Web of Science)

Fig. 2 An overview on the number of publications categorised by sources (from Web of Science)

levels is presented. The selection of cases is scoped emphasising quantitative and qualitative methods that are commonly and frequently used and accepted in engineering systems.

As such, the case studies presented in the following are primarily focused on modelling and simulation methodologies utilising network simulations, system dynamics and agent-based modelling in human-centric engineering systems including socio-technical and large-scale systems in domains such as energy, transportation, urban, cognitive, business, and governance systems. We believe the presented cases are a representative illustration of the approaches, methods, and tools used in studying the emergence within the engineering systems domain and could serve as a starting point in more profound exploration of the field.

Fig. 3 An overview on the number of publications categorised by institutions (from Web of Science)

Topics and cases that have been reviewed within the engineering systems design context include a range of emergent phenomena: from knowledge management at organisational level to innovative business models; from governance framework and mechanism design in infrastructure systems such as energy and transportation to resilient response and adaptation as well as team behaviour. Furthermore, applications of emergence in developing emergent technologies, information flow design and analysis, data-driven analysis and management, risk management, system of systems management, creativity, and human factors are presented.

To complete the overview, in addition to the phenomenon of emergence and application, the selected cases also present three fundamental modelling techniques: system dynamics, agent-based modelling, and network analysis.

Selected Case Studies

Nowadays, working in an engineering system requires the engineer to interact with a vast array of socio-economic complexities and 'externalities'. These complexities have many impacts, either positive or negative, on various aspects that are not necessarily a direct part of the engineered system or even a self-contained system or process under consideration (de Weck et al. 2011). Such externalities are, nevertheless, an integral part of the entire grand ecosystem in which the problem is defined. It used to be that engineers, even those who were beginning to understand that these externalities might matter, did not worry about them in their designs.

Understanding the impacts of these externalities must be factored into the engineering systems design process. Such inclusion is all about broadening the boundaries of the related fields of engineering systems. Particularly when due to the connectivity of different systems and their interactions, unintended consequences are becoming the norm, not the exception. In fact, we should be collectively aware that the challenges faced by the engineering systems community are even greater, as these externalities are more complex than was ever imagined. Hence, it requires a much broader perspective.

The discipline of engineering systems deals with various kinds of increases in scale, scope, and complexity dictated by the dynamics and emergent behaviour. The selection of case studies in this chapter is essentially concentrating on this increase in realms of the complex systems, which have engineered systems in their core. Complex engineering systems are not simply technical in nature but rely on people and their organisations for the design, manufacturing, and operation of the system among the other life cycle phases. They are influenced by the societal and physical context while influencing them at the same time.

These cases have been selected based on their relevance to the contextual background presented in the previous two sections and special considerations of the nature as mentioned earlier. In a more specific description, the purpose of the case reports included in this part is to shed light on the dynamics of interactions among agents in a complex socio-technical engineering system through empirical observations, qualitative considerations, and simulated models. Some other methodologies such as network analysis have also been considered depending on their contextual relevance.

To keep the reporting process for each case flexible and keep the independence of narration in accordance with the case and how it was originally narrated, each case will be described in a separate section. The structure and content of each sub-section are also dependent on the depth and details reported in each case. Therefore, keeping each case to its separate section provides readers with the opportunity of reading them separately and independently, based on their interest or familiarity with the context. This is essential as each case is chosen from a different domain and presents a different application of otherwise similar methodologies.

To cover a characteristic range of content, the selection criteria are categorised into the scope of coverage, sector or application, emergent phenomenon covered, and the analytical approach or methodology adopted. In terms of scope, the selected cases range from international organisations to state or regional, to urban, and cover also entities such as industrial and manufacturing companies or software development and design teams. With respect to sectors, the cases range from non-governmental to governmental in all levels (regional, state, and city), to the private sector from large-scale to mid-size organisations and teams.

In terms of scope, the cases include a global international level in case A, national state and regional levels in case B, national state and city levels in case C, industrial sector in case C, a company level in cases D and E, and a team level in case F.

The cases cover three topics: governance and security in cases A and D; learning and adaptation in non-governmental and engineering organisations is described in cases B and F; and business model innovation is addressed in cases C and E. With respect to methodological perspectives and modelling techniques, System Dynamics is utilised in cases A, D, E, F. Agent-Based Modelling is applied in cases C and F and Network Analysis is used in case B. See Table 1 for overview.

Table 1 Overview of research cases presented in engineering systems design literature

Case ID	Level and scope	Context	Emergent phenomenon	Applications	Modelling technique
Case A	Global organisation	Non-governmental organisation	Knowledge organisation	Information flow design and analysis	Network analysis
Case B	National state and region Automotive manufacturing company	Brazil vs Silicon Valley innovation system Innovation of business models in automotive industry	Business models innovation	Development of emergent technologies	Network analysis/ System dynamics
Case C	National state and city	Smart cities and urban systems	Governance of energy system behaviour	Data driven analysis and management	System dynamics
Case D	Industrial sector	Air transportation systems	Collaborative behavioural between competing companies	System of systems management	Agent-based modelling
Case E	Hardware manufacturing company	Cyber security	Resilient response	Risk management	System dynamics
Case F	Engineering teams	Software development Engineering design	Engineering team behaviour	Human factors and performance management	System dynamics/ Agent-based modelling

Case A: The Evolution of Knowledge Networks in an International Non-Governmental Organisation

Knowledge networks are created and reproduced through social interactions in the context of the specific community (Štorga et al. 2013) and have been acknowledged as major forms of knowledge exchange in professional and work-related settings, both within organisations and across organisational boundaries (Cohen and Prusak 2001). Research to explore the emergence of organisational knowledge structures has been conducted for many different asynchronous and synchronous practices of knowledge sharing with the focus on the phenomenon of the spontaneously emerging knowledge structures. For identifying emerging knowledge structures, studying e-mail exchanges as the key knowledge artefact and generally preferred communication tool of the knowledge workers in geographically distributed collaborative environments. The reason for such practice is that email is embedded in communicative processes and captures an increasing share of an organisation's total communication volume since individuals progressively appropriate their email client as a habitat in which they spend most of their workday (Roll 2004). For example, an analysis of interactions and knowledge sharing between individuals in design teams during an engineering systems design project and specifically how they dynamically balance design with managerial efforts was recently presented in Cash et al. (2019).

In case A, Štorga et al. explored how the formation, dissolution, and rewiring of the email-based knowledge structure triggers emergence of the organisational body of knowledge at a global scope within the context of an international non-governmental organisation (INGO) (Štorga et al. 2013). The modelling technique used was Network Analysis and the emergent phenomenon is the knowledge organisation. By analysing the dynamically changing knowledge structure configurations from e-mail of discussion lists (Fig. 4), research explored shifts within the organisational discourse on topics over time and identifies the influence of individuals within the social network on this shift. By linking the emergence of the knowledge structure and dynamics, the research proposes knowledge growth not as an invariant process affecting all participants equally but highlights the contextual and geographic influences of individual contributors in the overall emergence of the practice network's knowledge structure.

To analyse and understand this emergent knowledge structure over time, the authors first study the expansion dynamics of the knowledge and social networks to see if the process is random or uniform. Mapping the growth of the knowledge structure by drawing the change of network configuration throughout the studied period (Fig. 4), the authors were able to create a view on the evolution dynamics within the knowledge network. The authors further applied filtered viewpoints of the

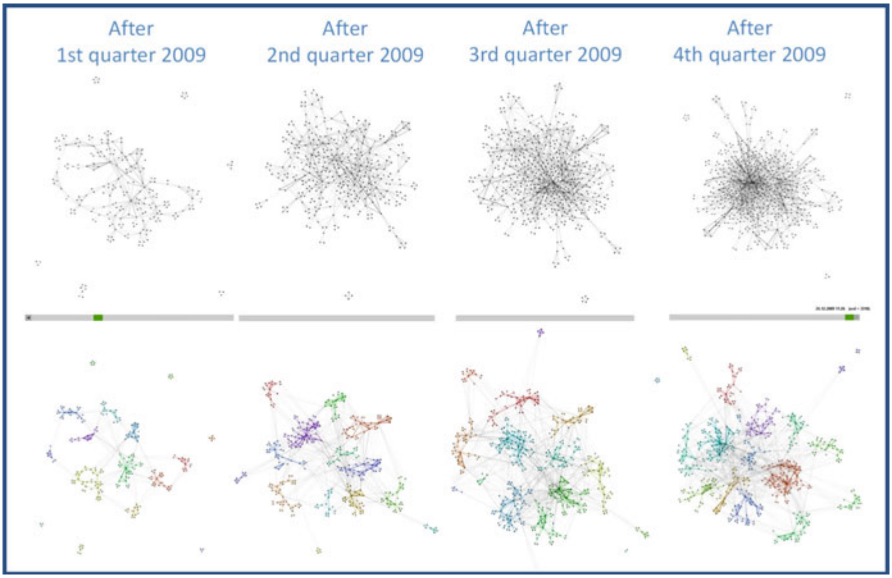

Fig. 4 Emergence of the content network depicted by network structure configuration after each quarter of the total observed period (Štorga et al. 2013)

evolving network, based on the higher context defined by specific topic and geographic location related to the contributing individual experience.

The results of this study indicate that the content structure of organisational knowledge networks exhibits hierarchical and centralised tendencies when it is considered through the evolving body of the email exchange. Many other organisational practice/knowledge networks also work based on issue/problem-response/solution dynamics, and it can be expected that the knowledge structure may have the form of the thematic communities and growth dynamics that were observed in this case study. Content hierarchy in this case was not seen as necessarily harmful since it allowed more efficient knowledge exchanges due to self-selection among the members of the organisation as the key driver of the studied emergent phenomenon.

At the same time, the social network analysis results suggested that the International Non-Governmental Organisation (INGO) studied exhibits non-hierarchical and decentralised structure for individuals contributing to the discussion lists. This kind of communication channel allows relatively easy access to the people regardless of where they are located and what their actual rank in the organisation is. The relatively small number of the contributions per person with different expertise also seems to have influenced the emergent phenomenon of the social grouping of the numerous people having knowledge gained from the geographically distributed location around the specific issues. This is different to discussions led by a small number of key experts who dominate the knowledge network and are influencing the centralisation of the communication.

For knowledge management practitioners, the approach presented in this research allows exploration of the dynamics of tacit to explicit knowledge, from individual to the group and from informal groups to the whole organisation. Since knowledge creation and dissemination in informal groups generally emerge spontaneous and random, the insight into the tendencies, styles, process, and structures may present great help for organisational knowledge managers. The support provided for comprehension and conceptualisation of the available knowledge captured and discovering the different viewpoints in conversation helps explain why specific knowledge structures are constructed the way they are and gives insight into where to intervene in order to direct information flow and thus knowledge structure evolution in a specific way if necessary.

Case B: System Dynamics for the Emergence of Business Model Innovation

When modelling dynamics of complex systems, bottom-up and top-down modelling should both be applied to get an overall understanding of the emergent properties and behaviour. Innovation as an outcome of the business market where the constituent elements, or agents/actors, are individuals, organisations, and institutions in hierarchical levels and with inherent characteristics (Filho and Heerdt 2018) is a good example for this. The interactions, or signals between the elements in this case, are the commercial transactions, the ideas and information exchanging, agreements, contracts, and other kinds of relations alike. The growth of innovation occurs between levels according to the evolution process and according to the path of the innovation, meaning that the choice of a wrong path may interrupt its flourishment. Research studies have shown that innovation in companies usually emerges from the lowest levels of the hierarchy (bottom-up processes). Emergent hierarchical processes are dynamic, evolutionary, and dependent on the lower-level agents and their interactions. At the same time, public or governmental policies, for example, are typically actions on the upper levels of the hierarchy (top-down processes). These policies may help the emergence of the innovation if they are well designed to respect the ongoing and self-reinforced dynamics of the innovation process coming from the lowest levels if such movements have emerged.

In Case B, when looking at the bottom-up processes, we can take corporate business model innovation (BMI) as a valuable means to create and maintain superior company performance (Moellers et al. 2019). A business model is most commonly considered as a structured and analytical model that defines the logic "by which the enterprise delivers value to customers, entices customers to pay for value, and converts those payments to profit" (Teece 2010).

Uncertainty concerning the viability of a new business model and the dynamics arising from complex interactions between its components causes significant difficulties to successful innovation. To produce a conceptual representation of the phenomenon, researchers connected system dynamics and BMI (de Reuver et al. 2013). Following that approach, Moellers et al. (2019) studied how system dynamics can support manager's understanding and decision-making along with different phases of the business model innovation process in development of the engineering systems. They applied an inductive multiple case study approach of five embedded cases within BMW (Moellers et al. 2019).

Within BMW, the use of system dynamics for BMI is referred to as 'Business (Model) Simulation' (BMS). BMS is an internally applied method that leverages engineering system dynamics to support the design and evaluation of business models and is divided into an iterative set of the six different phases, that is, *Sensing*, *Analysis*, *Transfer*, *Aggregation*, *Simulation*, and *Decision*. The presented study relies on data from five business model innovation (BMI) projects that were collated and analysed. Data sources included: (1) transcripts from semi-structured interviews; (2) archival data including system dynamics models, causal-loop-diagrams, brainstorming maps, interim and final presentations, project management artefacts; (3) observations from meetings, work periods, and internal discussions; (4) an indicative survey answered by 59 senior executives of BMW Financial Services; (5) e-mails, phone calls, and follow-up discussions with informants. Figure 5 provides an overview of the system dynamic model used for one of the cases.

As the results of the study, a set of the 11 propositions were created bridging the often-wide gulf between qualitative and quantitative researchers and facilitating future theory testing related to the different phases of the innovation process focused on business models. Consolidating the findings, it was concluded that system dynamics modelling enables corporate managers to reflect deeply about a business

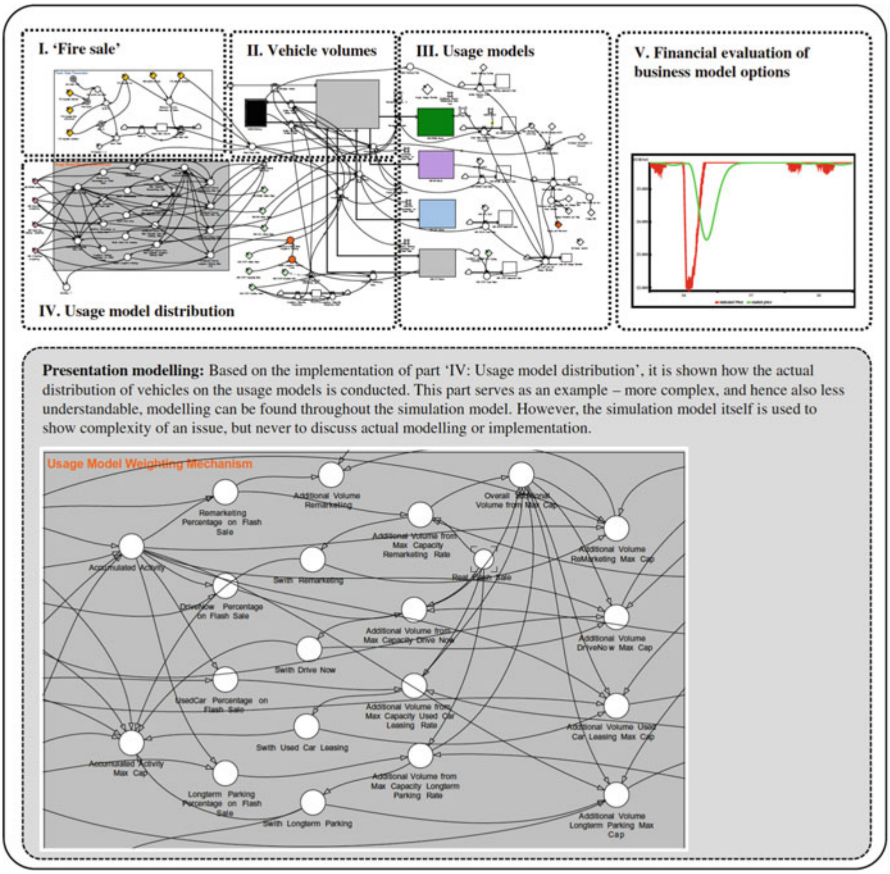

Fig. 5 Excerpt from the system dynamics models of one of the example cases from BMW (Moellers et al. 2019)

model's component architecture and consequently to develop higher dimensional cognitive representations of business innovation.

System dynamics simulations enhance decision makers' processing capabilities and allow them better to quantify the impact of different factors that are taken into account as relevant. When elaborating on potential business model innovation, the system dynamics (SD) models guide managers towards new shared understanding. During the modelling process, managers gain a thorough understanding of fine-grained dynamics inherent to the business model, for instance by varying the graphs of individual relationships and observing the consequences on other parts of the model in simulations. Among those being involved in this kind of practice, the SD model provides a neutral frame in which different mental models become transparent and can be openly discussed, which helps in the decision-making process.

As a different example, when looking from at top-down processes, as a case we may take the research of Filho and Heerdt (2018) who describes how innovation flourishes and emerges in a creative environment where the actors interact freely, to the extent that this environment is a complex adaptive system (Filho and Heerdt 2018). The research proposes the model, which considers innovation to be the result of a process that begins with the interaction between the fundamental elements of the economic environment; it emerges, or not, depending on the conditions of several levels of a process that must be scaled to reach success.

As the key part of the business innovation ecosystem, the authors considered educational institutions, governmental structures, foundations, associations, and similar organisations that interfere in the market. Despite the fact that, in general, these institutions are not in the centre of commercial transactions, they affect it profoundly. The effects can for instance be either for the best or for the worst when they contribute to interaction (such as education and communication systems), when they establish rules and taxes (like the acts of governmental departments), and when they improve the general infrastructure and facilities.

In Filho and Heerdt (2018), to elaborate on the hypothesis two cases were considered, one long-lasting success of innovation in Silicon Valley, which has resulted from a profound process of interaction between creative elements, and another case of the successive failures of Brazilian innovation, where public policies and growing investments have resulted in decreasing market novelties and lower quality of education. When studying the continuous success of Silicon Valley, Zhang (2003) found that the success of Silicon Valley demonstrates the continuous interaction of individuals and firms for decades, where new start-ups come from incumbent firms, and this fact does not create conflict, but by the contrary, benefits the game of innovation.

Zhang (2003) noticed that the founders of new start-ups were employees of incumbent firms, which shows the phenomenon of emergence coming from the interactions of individuals in a hierarchical system; that is to say, elements in one level interact and then come up to create a group at the next, higher level (Zhang 2003). Another interesting major finding of the study is that state and local government policies had a minor role in the early years of the growth of Silicon Valley, and its evolution is due to the culture of innovative thinking and industry – university networks, reinforced by a free flow of information between peers and even by competing firms.

Considering the consistent success of Silicon Valley throughout the years, several countries, institutions, and individuals have paid attention to what was happening there, and some have tried to mimic it. Brazil is one such example (Filho and Heerdt 2018). The theme of innovation took so much importance in Brazil during the 2000s and after that. The Brazilian case shows how several public and institutional policies, trying to direct and induce innovation, create opposite outcomes. The analysis presented in the research used the results of the Global Innovation Index (The Global Innovation Index n.d.), where Brazil consistently appears in a very low position, decreasing in the ranking yearly (Fig. 6), and discuss possible reason taking into account the elements of the innovation model.

Innovation in Brazil is getting worse yearly, even when the national approach to innovation spends more resources and efforts. In this case, top-down initiatives

Fig. 6 Global innovation index Brazilian ranking (Filho and Heerdt 2018)

interrupt the natural movements of the elements (and get the perverse result of discouraging these lowest-level systems actors). Unfortunately for the country, its government, institutions, and even universities insist on general policies, launching initiatives to induce lines of research to prioritise social and technological impact – typically a top-down initiative.

Both studies show limitation that the propositions of the innovation emergence model, despite being based on complex system theory, have no easy way to be proven, because there are no mathematical tools to simply test and confirm them nor field experiments to verify them. Such an approach differs significantly from experimental modes often associated with innovation. Therefore, it is hard to draw conclusions about the usefulness of system dynamics to support experimental research on innovation emergence in general. However, such a model has the practical and theoretical implication of bringing innovation as an object of study into the complex adaptive system field.

Case C: Governing Energy Behaviour in Smart Cities

Unintended consequences, both with positive and negative impacts, may appear as a result of behavioural patterns in a complex engineering system. Cities can be considered as manifestations of complexity, which has been captured in a variety of mathematical models from network and graph perspectives (Batty 2013) to social, economic, as well as cultural points of view.

That is why impacting collective patterns of behaviour through the governance of interactions among citizens is considered as a part of suggestive portfolio toward developing a cognitive city (Mostashari et al. 2011). This has been done for many subsections of urban systems. Particularly for the case of energy systems, it may have an impact on higher levels of society in the long term, that is, resilience and sustainability along with measures of productivity regarding the cost of energy.

A collection of educational plans through real-time feedback for awareness that is customised for receiving citizens through data-driven approaches from past and machine learning processes will impact personal patterns of behaviour. The same way social and institutional collaboration and cooperation based on design principles, which get updates from a similar type of feedback change the governing frameworks in a shorter period of time.

These forces collectively impact the quality of life in that society, while leading the city towards a sustainable economic, social, and environmental future. These are some of the emergent properties that Khansari et al. (2015a, b) delineated as results of a case study on energy behaviour in which systems thinking approaches and methodologies were utilised to develop a governing framework for technologically advance cities of future (Khansari et al. 2015a, b).

While their proposed layer-based framework for governance is developed with respect to energy behaviour, it can be applied as a governing guideline in other urban systems in cyber-physical cities of future as well as any other large-scale socio-technical system. The model applies three levels of human-institutional, physical, and data to create an understanding of how long-term emerging behavioural dynamics of the system could be. The objective is obviously to influence the trajectory towards desired circumstances both for agents and their society at large.

In line with that objective, they investigate the role of technology and its capability in changing energy consumption behaviour in both individuals and social levels. As a result, they adopted a survey-based methodology, aligned with the three aforementioned sub-layers in order to analyse the effect of technology as well as other individuals and social variables, in a households' energy consumption. Citizens of the Greater New York City have been considered in this case study.

However, what is of our interest is their modelling approach. They developed their model from a systems thinking perspective in which all factors from different layers of influence were identified and included. Figure 7 depicts their proposed layer-based model in which the relationship among each layer and their impacting factors are shown. Figure 8 summarises the result of their systems approach in

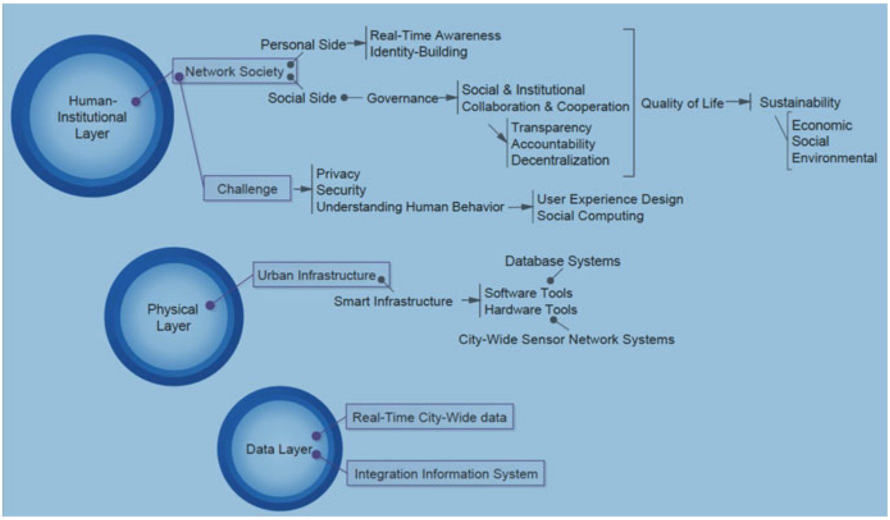

Fig. 7 A proposed layered framework for smart cities (Khansari et al. 2015a, b)

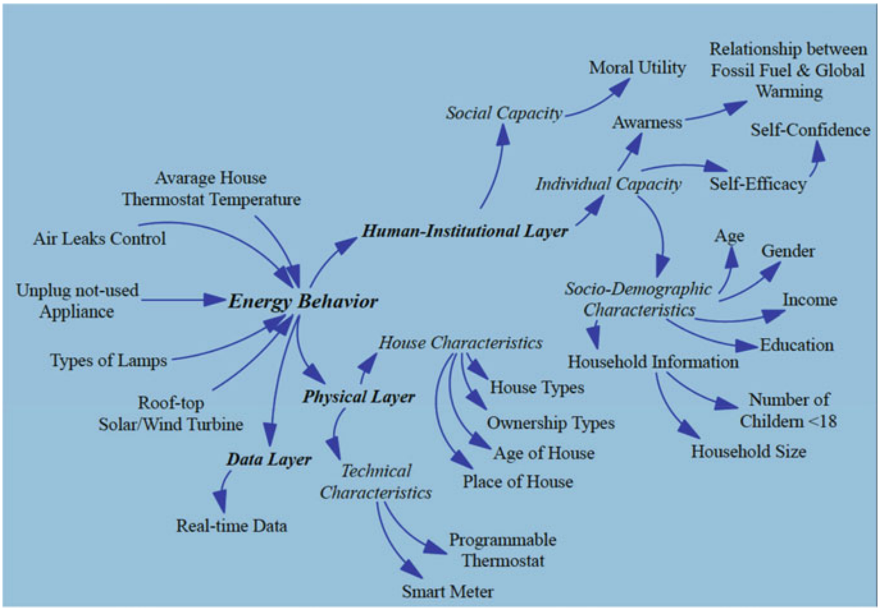

Fig. 8 Design of sensing dynamics (Khansari et al. 2015a, b)

understanding all the factors that have an impact on energy behaviour in relation to the layered framework. Such categorisation has been used for designing questions of the survey and for collecting data.

Case D: Mechanism Design to Influence Behavioural Dynamics in Air Transportation Systems

Dynamics of interactions among actors and organisations in network industries shape the dynamics of the entire market significantly. Lots of attention has focused particularly on collaboration and competition as these two forces project emergent properties over time. The conditions under which any two actors choose to collaborate instead of competing with one another are essential in the design and implementation of regulatory actions within such industries. This section reports on a research effort done by Darabi et al. (2014), in a particular case of competition and collaboration among airlines in the USA under different regulatory conditions (Darabi et al. 2014).

The research has adopted an agent-based simulation and modelling approach, which is fed by real data collected from a particular line of domestic flights between two major nodes (New York City to Los Angeles). Then, the validated model has been simulated, and the impact of different regulatory policies on the emergent properties of collective behaviour has been studied. This is a prevalent methodology in emergence studies as results of simulations could shed some light into the nonlinearity of interactions over time and show us a horizon for possibilities ahead. Such knowledge is suited for creating frameworks for future policy design activities.

The outcome of such research will provide us with a powerful toolset for investigating the dynamics of not only competition and collaboration, but any other interactive game that might be adopted by actors in an environment over time. That is why awareness of such research and its methodologies are necessary for anyone who is conducting research in the realm of emergence. As for this research, the results show how a set of developed models for both organisational strategies and governmental policies can have a significant impact on behavioural dynamics of the system.

In a more generic outlook beyond the topic of this case, emergent behaviour is considered as a systemic characteristic which arises from adaptive traits of the involving autonomous agents of the system (Grimm and Railsback 2005). Competition and collaboration dynamics in this sense is an emergent behaviour under study in this case, and this separates it from traditional game-theoretic models. First, the analysis in game-theoretic models leads to a mathematical model and an equation type of result will be the result, while behavioural dynamics is the subject of interest in such models. Second, most game-based approaches assume a constant payoff while in agent-based models' payoff is a dynamic function of ecosystem conditions, which in this case will be market.

In the case, nine different agent-based models of collaboration and competition under different regulations regimes and organisational strategies are simulated and documented for a single internal route between New York City and Los Angeles. The reason for limiting the model to one route is to eliminate the network effect on behavioural dynamics formation. Also, rather than developing a predictive tool, the focus of the case is on capabilities provided by agent-based modelling (ABM) in understanding behavioural dynamics in the airline industry under assumed conditions.

Agent-based modelling approaches, in general, are more appropriate when used as a scenario-based analysis or experiment as opposed to a forecasting tool.

The results for different games and regulative decisions are compared with each other below. Price, market share, and competition-collaboration dynamics are the variable of interest in these models. The dynamics of the airline prices in the market are presented in Fig. 9.

Similarly, the pattern of behavioural dynamics, namely, competitions and collaborations within these models, is different. The number of these interactions within each model and the relative pattern of them are summarised in Fig. 10, below.

Figure 11a summarises the results of simulations and the pattern of competitions for presumed conditions. These results imply that the number of competitions among organisations (airlines in this case) is highly sensitive to both market conditions and corporate strategies. Moreover, the pattern of competitions is similar within similar conditions. The pattern of collaborations in models is illustrated in Fig. 11b. This figure presents that dynamics of collaborations are similar in different models, which shows the financial profitability of collaboration for airlines in different settings.

The average of total wealth in different models is presented in Fig. 11c. The average wealth of the airlines will be maximised in the condition of multi-alliances and long-term decision making. This also highlights that creating alliances is not

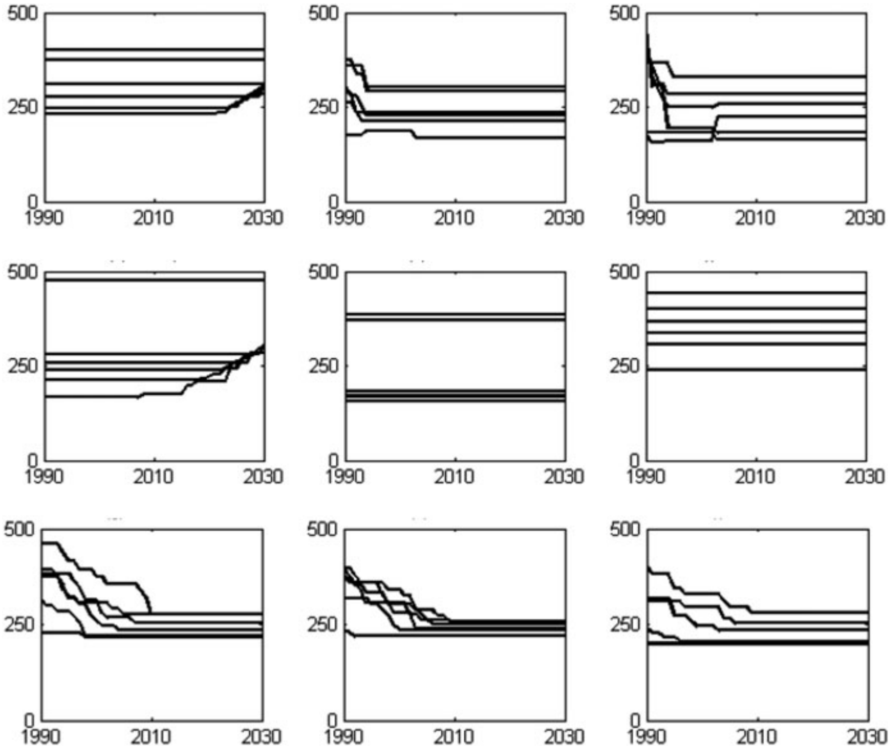

Fig. 9 The agents' pricing behaviour in different models (Darabi et al. 2014)

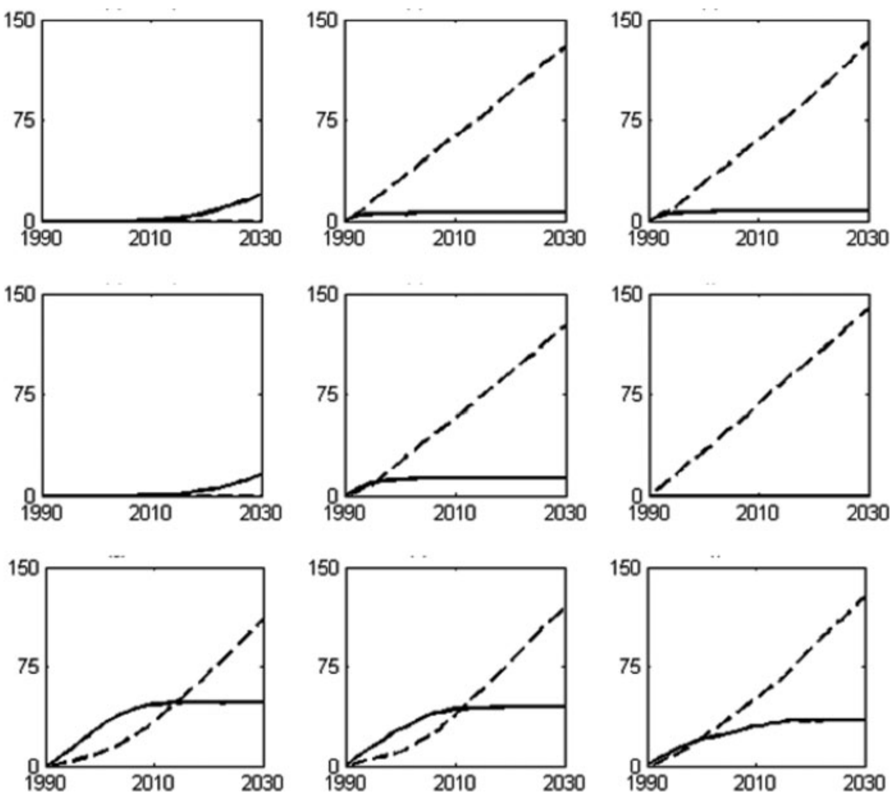

Fig. 10 The pattern of competition and collaboration in different models (Darabi et al. 2014)

necessarily financially profitable per se, but each alliance should be studied carefully, under each separate circumstances and conditions. In the single-year single-collaboration model, for example, the airline industry will be bankrupt over the time horizon of modelling.

Implications of the research conducted in this case represent the results of nine different models. The first conclusion is that competition in the airlines industry is highly sensitive to regulatory policies and strategies of each autonomous actor. Conversely, the conditions of the market do not have a significant influence on attracting collaborative behaviour in the network system. The average of total wealth for the airlines exhibits path-dependent behaviour. Therefore, the total wealth of actors at the end of the simulation is highly dependent on their initial decisions.

Case E: Dynamics of a Resilient Response to an Intellectual Property Cyber-Attack

System dynamics modelling empowers a more comprehensive and dynamic causal understanding by highlighting the interdependences, interactions, and

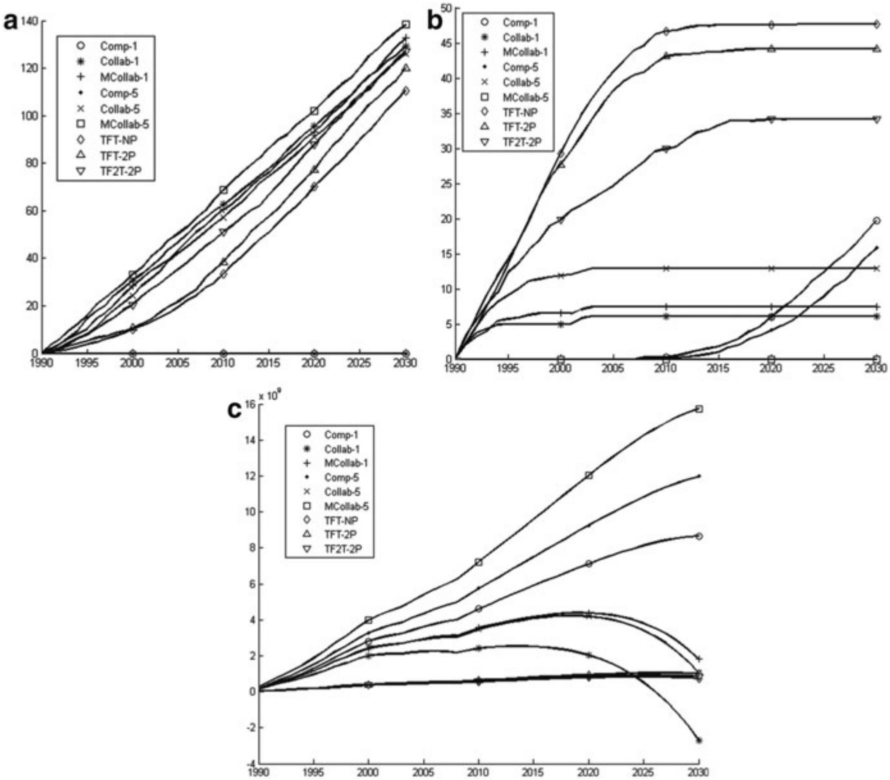

Fig. 11 Results of comparison among collaborative and competitive regulations in different model conditions (Darabi et al. 2014; INCOSE n.d.)

interrelationships in the complex engineering system. The particular capability of this approach is in capturing the emergent properties of interactions and behavioural outcomes of a system in a specific time scale through defining the multi-dimensional causal relationships, potential delays, and feedback mechanisms from all perspectives (Khansari et al. 2015a, b). This approach has frequently been used for capturing and analysing dynamics in a variety of systems, particularly in large-scale systems such as supply chains as well as in resilient responses to disruptions.

In a combinatorial context, shocks and disruptions in the supply chain both in physical and managerial operations create a unique situation for modelling emergence. Sepulveda and Khan (2017) have focused on a case in this context (Sepulveda and Khan 2017), particularly on the impact of disruptions in the digital information and Information Technology (IT) protection on supply chains. In resilience studies, the company losses will depend on many factors including the coherence and swiftness of response, in the face of disruption. One challenge is to take the existing qualitative frameworks for resilience design and bring them to life with quantification of variable and particularly within the context of time. This provides a tool for modelling the dynamics of interactions and hence, the possibility of the system's resilient response.

The research done is focused on addressing this challenge by developing a system dynamics model. A real-life case of resilient response is adopted, which covers a series of activities after a cyber-attack. A reaction mechanism is consequently proposed based on the results of the simulated model. Such findings similarly to other cases presented in this chapter may be used in a portfolio of decisions that can be used in governing activities to face emergent properties of any given undesired event.

Supply chain responses over time in the face of shocks have been addressed by the resilience frameworks proposed before. Particularly from a mathematical modelling perspective which follows the depth and duration of impact over time, in what is called "disruption curve." The major approach is to keep the curve in a particular format in which the impact of disruption on the performance becomes less and in a shorter time.

However, the impact of disturbance through theft of Intellectual Property (IP) of an organisation in an IT context is trickier to tackle. IP is a particular asset, which is increasingly subject of theft through the use of IT in its transfer, storage, and development coordination processes. It is an essential centre for innovation, business growth, and competitiveness of companies. The contribution of the case is concentrated on IP theft resulting from a cyber-attack. The idea is to identify the organisational structures that make it resilient in face of such circumstances.

This is done through a system dynamics model and analytical approaches that come along with this tool and methodology. When the model is created, tested, and validated, the results can be tested for a variety of changes in parameters of the model and findings of such sensitivity analysis will contribute to the system's performance evolution over time. In addition to that, in the process of building the dynamic model a framework for investigating into the emergence of any given disturbance can be designed.

The subject of the case is a large producer of hardware, which becomes a victim of a cyber-breach shortly before a product launch. The effect of the attack was IP theft relating to about half of their production lines. The stolen information, if used maliciously, will destroy the company's business in favour of its competitors. The organisation similarly to any other in the face of disruption has three stages reaction: time of the accident, managing impact, and moving back to normalcy.

In this process, a team for crisis management along with research scientists worked to minimise the effects of this attack, which affected the company's production. A cyber-security consulting firm was also hired to investigate the leak and secure from failure as well as future similar attacks. A law consulting firm was commissioned to work on potential legal ramifications of the theft. Finally, a public relations (PR) firm got involved in protecting the company's fame and managing the impact of the news on media. At the end of all these efforts, the company was able to maintain the production processes while upgraded its IT infrastructure, archived and secured its IP inventories. These, however, are not of this chapter's interest. The most relevant part of this case is the approach it adopted to model emergent properties of such disruptive incident.

Figure 12 depicts some of the causal loop diagrams that have been used in the case to model the dynamics of the system and summary of the simulation's results. The model covers the resilient response to a cyber-attack imposed on the company.

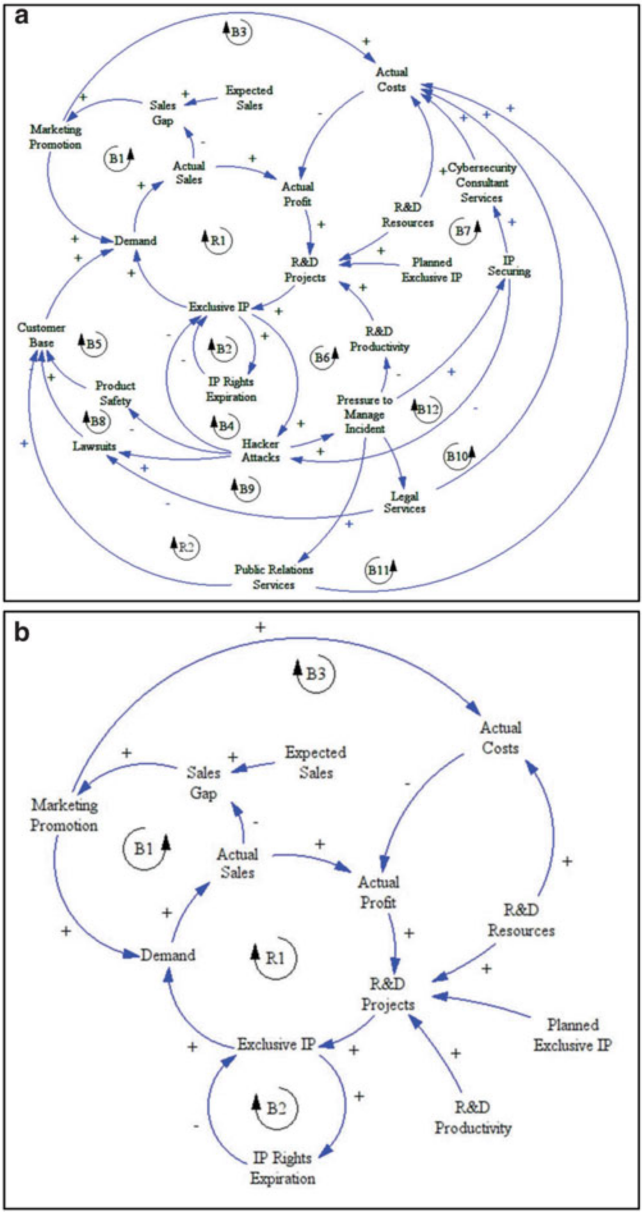

Fig. 12 (continued)

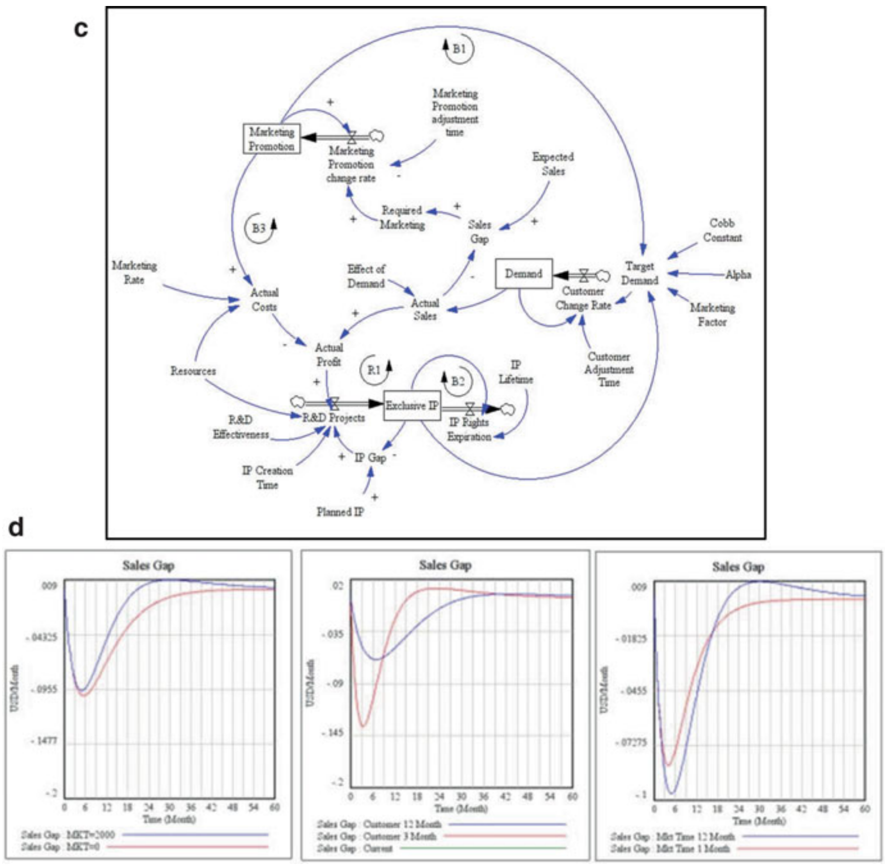

Fig. 12 Causal loop diagrams of the system dynamics model and simulation results (Sepulveda and Khan 2017)

The case shows how to capture emergent properties of an unknown dynamics; a series of cross-disciplinary processes and a way to capture their interactions over time are required. If the right approach and effective tools are adopted, we will be enabled to understand the needed structure as well as essential regulations for interaction in any given system for showing resilient behaviour in the face of disruptive events.

This may be used as a framework to design policies for resilient governance to face exogenous variables and particularly disruptive shocks. Such governance approaches are crucial for continuity in any type of systems. In complex systems, resilient behaviour is considered a part of the system's emergent properties. Yet, having a governing structure will guide us in the designing phases of engineered systems.

System dynamics models provide us with opportunities to capture the long-term effects of a shock to any given system. The capabilities that come with simulation will also enable us to test possibilities of future through a change of policies adopted in different phases. A combination of these immediate short-term operational decisions and long-term policies can potentially minimise the overall cost of disruption. They can also help to create the right incentive structures that trigger a resilient response throughout the evolving lifecycle of disruption.

Case F: Team Behaviour Emergence – Empirical and Simulation Perspectives

From an organisational management perspective when it comes to the challenges like new customer requirements, market dynamics, mergers, and technological innovation, of particular interest is how teams can adapt to improve their reaction to such changes. According to the literature, there are different states of adaptation, but we still lack a proper understanding of how it emerges. When investigating team behaviour emergence in teams developing engineering systems, scholars often rely on the theory of complex adaptive systems (CASs) (Alaa and Fitzgerald 2013). Non-linearity, emergence, and self-organisation are major characteristics of CAS.

While self-organisation is described as a process, emergence is the result of such a process (McCarthy et al. 2006). Within teams, emergence is a phenomenon that "is a pattern of behaviour, a coherent structure or a state between individuals" (Curşeu 2006). Emergent states can manifest themselves in different forms within a team, such as team agility, team trust, team cognition, or team learning. Emergent states are defined as "constructs that characterise properties of a team that are typically dynamic in nature and vary as a function of team context, input, processes and outcomes" (Marks et al. 2001).

In one of the examples of such research, Werder et al. (Werder and Maedche 2018) in their empirical study seek to identify the conditions of team dynamics that explain emergent states of team agility. Contrary to prior studies, their work identifies agility as a team-level phenomenon. Based on the findings in the literature, they proposed conceptual framework for studying team agility states for the software development teams (Fig. 13) and investigated the proposed framework empirically by a holistic multi-case study in three different organisations (small, medium, and large medium size software development companies).

When mapped to the CAS perspective, the team agility comprises three systems, that is, the local, global, and contextual system. In the local system, the study finds job clarity and individual experience to enhance self-organisation. Particularly important is individual's experience as one of the team's critical resources that can either facilitate or prevent autonomy. Within the global system, goal interdependence and user research improve self-organisation.

Within the contextual system, management support and development length can help the team to self-organise and orient. Technology access and team task complexity are mandatory conditions within the context of software development teams. Team task complexity inhibits team autonomy by introducing chaos and limiting

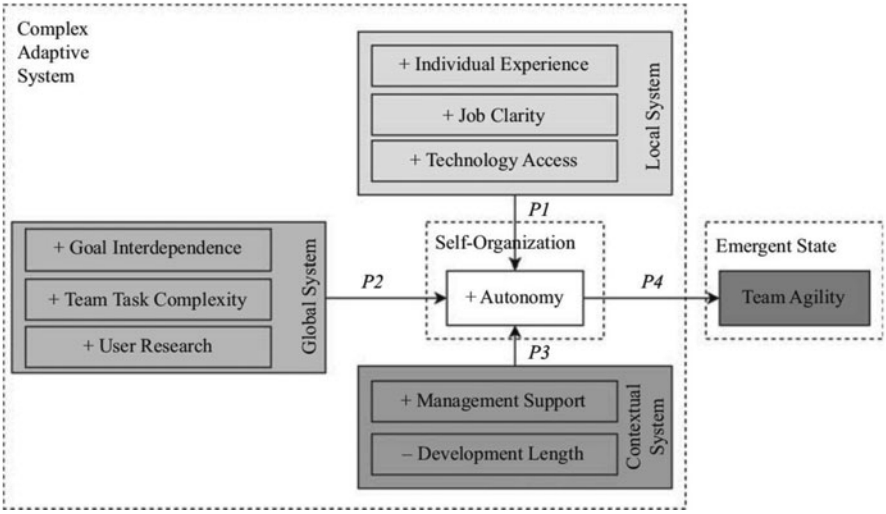

Fig. 13 Team agility framework proposed (Werder and Maedche 2018)

their ability to create redundancies. Teams that develop highly complex products are less autonomous.

The authors found two practical implications of the study (Werder and Maedche 2018). First, by the proposed framework organisations receive a list of influential characteristics and can leverage the characteristics in the form of a checklist to assess the emergent status of the teams. As a result, they can investigate weak characteristics and strengthen others to increase the agility of the team. This is especially useful for teams struggling to move from a process-cantered view of agility towards a mature and cost-effective state of agility. Second, organisations become aware of the importance of a common and joint objective. Goal interdependence is one means to embed such objectives into an organisation formally. They can also develop organically by adopting user research. For those cases where the organisation lacks the expertise to conduct user research, consulting agencies, or experts can extend the team's expertise. They also provide another view to the issues and challenges faced, allowing the organisation to benefit from their experience and expertise.

A complementary approach to studying team behaviour emergence is by application of computational simulations that could provide valuable insights into emergent team properties and behaviours difficult to study in real-world experiments (e.g., change in cognitive behaviour of team members over long periods). One of the recent models using the agent-based paradigm to develop a *computational laboratory* for studying engineering design teams is reported in research of Perišić et al. (2019a, b, c). In their work, individuals are represented with computational agents that are based on social and cognitive theories and are capable of learning (Fig. 14).

This provides agents with the capability to change over time, offering a means to simulate and study the dynamic of the adaptation processes of engineering design

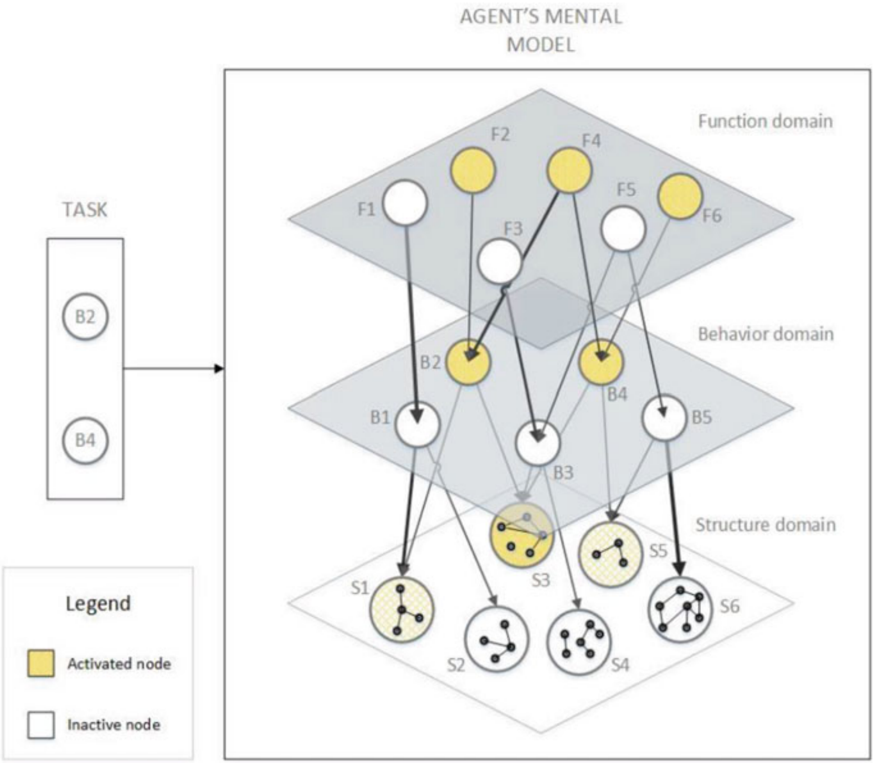

Fig. 14 Agents' mental model (Perišić et al. 2019a, b, c)

teams. The developed computational framework was used to test different hypotheses related to the emergent patterns in team learning (Perišić et al. 2019a, b, c), problem/solution space exploration (Perišić et al. 2019a, b, c), and team creativity (Perišić et al. 2019a, b, c) with some interesting and surprising findings as was the emergence of the situated novelty, the concept that was known in fashion or healthcare domains but was not studied as a dynamic phenomenon in the previous research of the engineering creativity.

In their study of the differences between inexperienced and experienced teams regarding their patterns in problem-solution space exploration (Perišić et al. 2019a, b, c), the authors tested the hypotheses that experts converge to the solution quicker and spend more time exploring the solution space. The computational simulation was designed as a set of the 250 experiments, each consisting of the four tasks performed by inexperienced agents (novices) vs experienced agents (experts). The performance on the initial task was not included in the results and statistics, as it served an "expert" agent team gaining experience which would distinguish it from an inexperienced, "novice" team of agents. To study the agent's exploration of problem and solution space in greater depth, the team's communication during the tasks was recorded and analysed. Moving Problem-Solution (P-S) indicator as

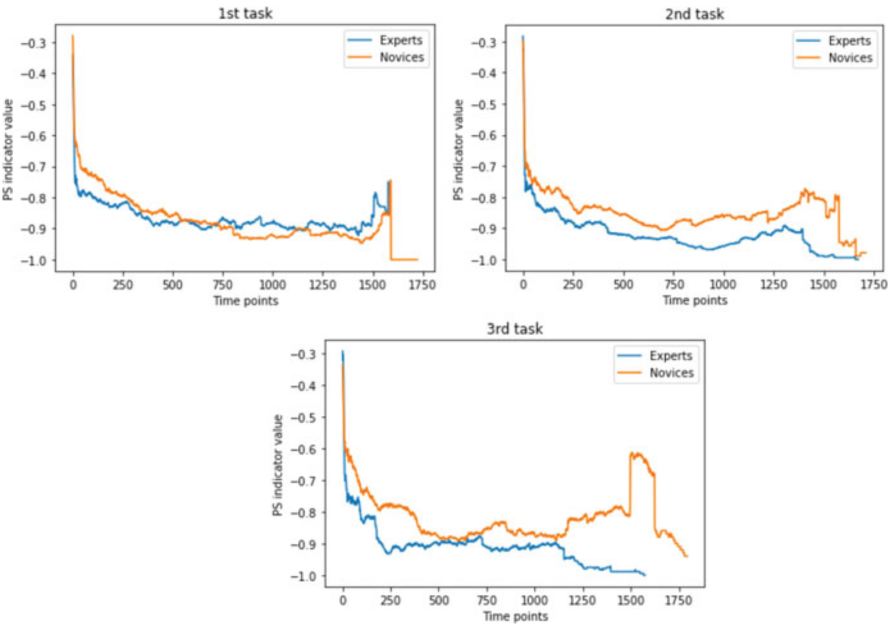

Fig. 15 Comparison of the average moving P-S indicator (Perišić et al. 2019a, b, c)

defined in the work of Gero et al. (2013) was used for the representation of the analysis results.

The results of the simulations (Fig. 15) show that there are strong significant differences in steps needed by experts and novices to reach a solution, with the experts taking noticeably fewer steps. As the difficulty of the tasks increases, for both, novices and experts, the average number of steps needed to find a solution increases from task T1 to task T3. However, it can be observed that the rate at which a number of steps increases is lower for the experienced agents, indicating that previous experience provided them with knowledge, which is reused in subsequent tasks, while novice agents have to spend additional time learning it.

When considering the average distribution of the Function-Behaviour-Structure design processes (used to model the knowledge space) within the simulation (Fig. 16), the rate at which expert agents communicate links and structures remains mostly the same. At the same time, the rate at which they create new structures almost doubles throughout the tasks.

This indicates the increased ability to transfer to (and explore) the solution space. As the tasks become more difficult, the inexperienced agents communicate less distinct structures and links, which signifies that knowledge nodes become more difficult to activate and knowledge links take more time steps to ground. Both previously described findings emerging from the simulations and analysis are in accordance with the literature.

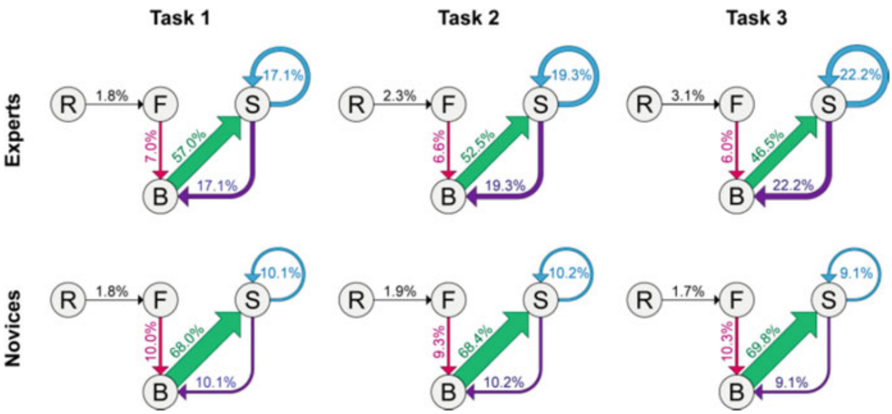

Fig. 16 Average distributions of Function-Behaviour-Structure design processes for each task group (Perišić et al. 2019a, b, c)

Despite the limitations, this cognitively based agent model has shown its capacity to model team emergent behaviour and has the capability of being used to test different hypotheses. It could be used to study the effect of churn on team behaviour, the impact of team structure on performance, the formation of de facto sub-teams, and the effect of design space generation, which can be used as a proxy for design creativity.

Computational simulation tools used to study team behaviour can be used to produce results of a very large set of simulations, the analyses of which could form the basis of a big data learning activity to uncover other systemic behaviours that are not currently being spotted. This enables exploration and discovery of the emergent patterns within the team's behaviour that would not be possible by conducting the research using observations of the real-world teams.

Reflections

We live in an emergent universe in which it is difficult, if not impossible, to identify any existing scientific problem or study any complex behaviour that is not emergent. Dynamics and emergence are iconic properties of complex engineering systems. In a sense, they are both by products of complexity. They are also connected and often coexist as properties of and extensions to the systems as a whole. Emergent properties in systems are the product of dynamics among actors or elements that interact within their respective system boundaries. This is mainly due to the concept of autonomy among system components. A system in which actors have a certain level of autonomy in a behavioural mode often generates unpredictable and non-linear trajectories in collective behaviour over time.

That is why emergent properties of a system are essential to be identified. It is imperative to understand the impacts of unknown factors, generated by complexity, on collective behaviour outcomes of the system. However, some researchers have a different argument in which they consider ambiguity as a critical feature of the behaviour that is generated in complex engineering systems. They believe emergence is a value reference to lack of understanding about the behaviour of the systems of interest at large (Mitchell 2009).

Regardless of contradicting takes on this matter, as it is apparent in the literature and cases presented in this chapter, modelling and simulation methodologies are universally accepted tools for researching dynamics of behaviour in complex engineering systems. This can be done in two different schools of thoughts. Agent-based models can appropriately model a systems behavioural dynamics at the micro level and from a bottom-up perspective, while system dynamics captures the behavioural patterns of macro level interactions and from a top-down perspective.

Both models, if used effectively, give us a reliable understanding of what to expect behaviourally in the long term or cases of disruptive changes, of the system's outcome. This is, in another sense, understanding the emergent properties of the system (Khansari et al. 2015a, b). Changes in variables or structures of the model can provide us with a range of different possibilities as an outcome and some of these possibilities calculated through such computational methodologies can never be predicted using mathematical models. That is why most cases covered in previous sections used modelling approaches for solving the problems of their complex system under study.

Another observation in reviewing the cases indicates the importance of decisions or policymaking, which is the core of the problems the cases were trying to address. In a more generic sense, one of the important reasons for learning about the dynamics and emergence of complex engineering systems relates to the concept of governance. While it is almost impossible to control for all nonlinearity that emerges from dynamics in a complex engineering system, we strive to influence certain desired outcomes to occur as opposed to others, which might be costly for the system or even become an existential threat for its longevity. Creating a structure for influence, according to some perspectives, is equivalent to the design of a governing framework for any complex system.

This is even more applicable when we are talking about socio-technical engineering systems. In this context, system governance refers to a societal function among the stakeholders, who are the same autonomous agents and entities that lead the system toward an outcome, through the dynamics of their interactions (Young 2013). The assumption is that all these players define such an outcome and there are defined measures for its desirability. Some complex systems exhibit self-organising properties, which perform as governing structures created due to their dynamics over time. This is indeed another emergent property of complex systems (Gunderson and Holling 2002), for which planning is still needed at the systems' design phase.

Moreover, a sensitivity analysis run on a modelled version of a system can provide designers and analysts of any given system with mechanisms for governing dynamics and the emergence of outcomes. This is another benefit of the adoption of modelling and simulation methodologies. It provides the systems designers or analysts with leverage in weaving resilience into the fibres of the system under study through a system's governance structure.

The behavioural response of societal or other human-centric systems in the face of adversities, shocks and disruptive events from outside their boundaries or changes that are brought about from unintended dynamics among agents is of paramount importance. The stability and autonomous reversal of undesired shocks are indeed more crucial for the sustainment of a system as opposed to its structures or order under which its components belong, act, and cooperate. Rules of all those games can change along with the behaviour of each agent in a steady state. At the end, the collective behaviour of the same agents within existing or developing structures that give way to resilience as one manifestation of emergence (Erol et al. 2010).

Resilience becomes more problematic in complex and especially human-centric systems when bifurcations emerge instead of oscillation, which bounces the system back to its near-normal capacity. Designing for an adaptive governance framework is inevitable for such circumstances instead of relying on the emergence of self-organisation following the disruptive change. In parallel to challenges of dynamics, collective action issues are also a part of the problem at the levels of societal systems.

These outcomes of collective action including but not limited to problematic issues often emerge out of micro motives and consequently produce different kinds of macro behaviour that is systemically undesirable in the sense that none of the stakeholders of the system benefit from its outcomes (Schelling 2006). Situations involving the tragedy of the commons concerning the provision of public goods are a notable example of such a phenomenon (Hardin 1968).

Another problem that arises from agent-driven micro motives has roots in the cultural or behavioural norms built over time. These norms often create what is known as ‘path dependency’, which is a tendency in certain behavioural continuities. Path-dependent systems have known patterns of behaviour. They often proceed along the same predetermined paths in the contingency of external forces. In other words, they show expected behaviour in the face of external factors through sorting them into known inputs and responding to them in their known ways depending on past experiences.

These reactions are often emergent properties of micro motives that have shaped and solidified over time. Path dependencies are not necessarily harmful to systems but may also lead to collectively undesirable outcomes even when those engaged in the relevant actions are aware of the situation. This is another reason why it is crucial to design a model-based governing framework through which all possibilities of path dependency are identified, understood, and planned. Planning in this context requires developing a portfolio of policies and a contingency plan for adoption by the system’s governing body.

Ultimately, attention should be on the design and operationalisation of the governance structure in systems as a meta-concept for inclusion. Such a governance structure should ideally be a framework that animates all these restrictive policies, incentivisation motives for interaction, and dynamics generation. Through a platform, it would enable collaborative consensus that influences the achievement of collectively satisficing outcomes. This refers to the fundamental finding that an effective governance framework influences desired emergence through incentivising required dynamics among agents of complex systems, over time.

Conclusions

The topics of dynamics and emergence in systems come with many uncertainties as the nature of these concepts requires. That is why the purpose of this chapter was to shed light on unknown sides of these topics through experiences that other researchers had with them in practice. The first sections are dedicated to definitions of terms and concepts referred to in the following parts. This is also imperative in defining the scope of literature and developing a collective understanding of concepts. The next step is to choose relevant domains and applications within the defined context. This iterative method brought us to a selection of case studies. As part of the required characteristics, we selected cases whose methodologies are in the realm of modelling and simulations, particularly systems thinking approaches, including system dynamics, agent-based models, and network analysis. Moreover, the results of selected studies are related to further crucial concepts, namely, governance, resilience, and design. The presented cases, therefore, introduce a range of research in the field as a guideline for governing architecture of systems, setting rules and regulations, as well as adopting policies that embrace resilience as an emergent property of complex systems, and can be incorporated into the system's trajectory of response, by design.

Cross-References

- ▶ Architecting Engineering Systems: Designing Critical Interfaces
- ▶ Asking Effective Questions: Awareness of Bias in Designerly Thinking
- ▶ Designing for Technical Behaviour
- ▶ Engineering Systems Interventions in Practice: Cases from Healthcare and Transport
- ▶ Flexibility and Real Options in Engineering Systems Design
- ▶ Formulating Engineering Systems Requirements
- ▶ Properties of Engineering Systems
- ▶ Research Methods for Supporting Engineering Systems Design
- ▶ Systems Thinking: Practical Insights on Systems-Led Design in Socio-Technical Engineering Systems
- ▶ Technical and Social Complexity
- ▶ The Evolution of Complex Engineering Systems

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Designing for Emergent Safety in Engineering Systems

19

J. Robert Taylor and Igor Kozine

Contents

Abstract

This chapter is about emergent safety hazards in engineering systems. These hazards are those that emerge from a system without arising from any part of the system alone, but because of interactions between parts. We distinguish two approaches to analysing engineering systems: one is to view them as socio-technical, and the other is to consider them as cyber-physical systems. We illustrate a great deal of emergent

J. R. Taylor
Department of Technology, Management and Economics, DTU-Technical University of Denmark, Kongens Lyngby, Denmark

I. Kozine (✉)
Department of Technology, Management and Economics, DTU-Technical University of Denmark, Kongens Lyngby, Denmark

Southern University of Denmark, Odense, Denmark
e-mail: igko@health.sdu.dk

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hazardous behaviours and phenomena due to unknown accident physics, malign actions, chemistry, and biology and due to deficiencies in managements and organisations. The method that follows the socio-technical view consists in the representation of a system by sequential functionally unrelated processes that can in reality influence the performance of each other via sneak paths. The method that follows the cyber-physical systems view focuses on the analysis of control loops (feedback, feedforward, positive, and negative) and, especially, interrelated loops. The chapter explores also the realm of security threats due to malign actions that can trigger safety-threatening events. And finally it gives general guidance for avoiding and eliminating safety hazards when designing engineering systems.

Keywords

Cyber-physical safety · Emergence · Engineering systems · Hazard · Safety · Socio-technical safety · Threat

Introduction

Systems design has progressed a long way since the beginning of the industrial revolution and has been propelled as a separate discipline since the beginning of systems design during the Second World War. We now use personal devices with tens of millions of components and depend on large-scale systems with trillions of components. That these engineering systems work at all is amazing, and that they work dependably most of the time is even more so. But they do fail, and for large systems, the effects can be catastrophic. An immediate example reported in *The Guardian* is the shutdown of Heathrow airport on 7 August 2019 for several days, with tens of thousands of people stranded, because of a software error. In some fields, such as administrative data processing systems, failures are frequent. Moreover, while many of these failures may be seen as unintended hazards, others are due to malign interference broadening the task to design engineering systems for safety to include the task of designing them also for security.

Looking to the future, our engineering systems, such as supplies of necessities for life, electrical power, water, food and warmth, financial systems, and communication systems, are becoming increasingly interconnected, increasingly complex, with increasingly serious consequences of failure. As just another simple example (personal observation), when the credit card payments system failed in a small town, people were unable to buy food. Society had become virtually cashless, and while some could drive to other towns to buy food, others had to depend on their stocks in the freezer. The largest problem was for those who could not buy medicines. The problem was solved within two days, but the vulnerability of our engineering systems was illustrated. The area affected could have been much larger and the downtime much longer. Technically, it is possible for such events to affect entire countries and to overwhelm the capabilities of emergency services.

Modern systems become more complicated because of the desire or need for efficiency, convenience, and comfort. Hospitals for very large areas, even large countries, become interconnected so that patient data can be shared between general practitioners, hospitals, and specialists. Payment systems become interconnected because this is a necessary part of the need for universal access. Electrical power systems become more connected because of the need to balance demand with solar and wind power production. Financial systems are necessarily connected in order to be able to transfer funds. All of this interconnection becomes possible because of data processing and computer-based control. The large-scale engineering systems of the present and the future are those "that integrate information technologies, real-time control subsystems, physical components and human operators to influence physical processes by means of cooperative and (semi)automated control functions" (Guzman et al. 2019). They are called cyber-physical systems.

The definition can be extended by including in the scope of analysis the organisational structure and people in the outer environment. In this case, we can refer to systems of this type as socio-technical systems. The distinction between the two is important, as we can expect different types of emergent hazards for each class and, sequentially, different types of models for identifying emergent hazards.

Developments in technology, as well as our ability to identify and control failure, have enabled extremely large systems to be designed and operated. Traditional risk analysis methods allow the routine component failures and single person errors to be identified. As design progresses in this way, "emergent hazards" become increasingly the most important contributors to risk, and this introduces problems for the designer.

In design for safety, we can recognise the following classes of phenomena and behaviours that we can term as emergent hazards:

- Hazardous behaviours which arise from complex systems in unexpected ways, due to limitations in our analysis methods
- Emergent hazards due to creative and possibly hitherto unseen malign action
- Completely new and hitherto unseen or unrecognised hazardous phenomena
- Hazardous behaviours which arise from systems in the absence of component failures or errors of individual user or maintenance actions

Each of these classes presents problems in analysis, and most require new approaches in safety assessment.

An emergent complex system hazard can be defined as a "pathological" (often unpredictable) failure behaviour that is manifested in complex, highly coupled systems, possibly in catastrophic ways. Emergent behaviour in these systems cannot be predicted by examination of system's individual parts. The phrase "the whole is more than the sum of its parts" occurs often to explain what systems thinking is. In line with systems thinking, complex systems emergent behaviours can also be defined as those that emerge from a system without arising from any part of the system alone, but because of interactions between parts.

What does it really mean that the whole is more than the sum of its parts?

Simple cooperation, for example, can be viewed as the joining of similar labour efforts on some mechanical task. We can expect that the practical outcome of the activity may be greater than the sum total of these labour efforts. The organised whole may well be practically greater than the sum of its parts. As Bogdanov (1996) exemplifies, "experience gained in the French colonial wars in Northern Africa evidences that, being equally armed, an average Arabian soldier in one-to-one clash is just as good as an average French soldier, but a detachment of 200 French soldiers is stronger than 300–400 Arabian fighting men". In fact, the performance of a poorly organised whole can be less than the sum of the efforts.

This means that if we know the performance characteristics of all parts of a system, this is nevertheless not a sufficient prerequisite to conclude on the performance characteristic of the system. The individual performances either can amplify each other when acting as a unity or can reduce the total sum of the performances. The total performance in a general case is a non-linear function of the system's parts. This is exactly the non-linearity in the outcome performance that stems from complexity. To predict the effect of non-linear behaviour is a challenge for designers of engineering systems.

Emergent hazards and threats in engineering become a topic of importance that is motivated by the large consequences witnessed and the difficulty of identifying and preventing the hazards of this type. Published literature on the topic is rather scarce. However, some studies have been carried out. A good summary of emergent behaviour in systems is described by Fromm (2005). Netherlands Organisation for Applied Scientific Research, TNO, have described emergent risks arising from the use of robots in the workplace (Steijn et al. 2016). De Jong and Blom (2006) described methods for identifying emergent hazards in engineering systems and the use of hazards and operability (HAZOP) analysis in complex engineering systems, specifically in air traffic control.

Pereira and Howard (2006) employed a system theoretic process analysis (STPA) method (Leveson and Thomas 2018) to hazards analysis for ballistic missile defence systems. They state "safety is an emergent property of the systems arising from interactions between software, hardware and humans. Safety is maintained by placing constraints on the behaviour of the systems components". Their approach looks for emergent hazards arising from a lack of control systems enforcing safety constraints, inadequate control, inadequate or missing feedback, inadequate execution of control actions, and inadequate enforcement of constraints.

Here we provide a review of engineering emergent hazards and methods to identify them. As information and computer technologies are tightly integrated into modern engineering systems, malign efforts become yet another cause of emergent hazardous behaviours. When referring to intentional hazards, we call them security threats. Methods for their identification and avoidance are a major topic in itself and not part of this chapter. However, the influence of security on safety and propagation of security issues into safety issues is acknowledged as a contributor to emergent hazards, and in this chapter, a first exploration is given.

This chapter is organised as follows. Section "Emergent Hazards in Engineering Systems" provides evidence on the multifaceted nature of emergent hazards and security threats, and that may result in catastrophic consequences. Section "Techniques to Identify Hazardous Behaviours in Systems" gives a brief overview of extant methods to identify hazards in engineering systems, their weaknesses when applied to engineering systems, and existing techniques to capture emergent hazards in engineering systems. Section "Avoiding and Eliminating

Emergent Hazards" provides ways of avoiding and eliminating emergent hazards when designing engineering systems. The concluding section "Conclusions" is a summary of the described study.

Emergent Hazards in Engineering Systems

We distinguish two approaches to analysing engineering systems: one is to view them as socio-technical systems, and the other is to consider them as cyber-physical systems. When considering engineering systems as socio-technical for the identification of hazards and threats, and their causes and consequences, we need to take account of human errors, different cultures, and behaviours in organisations, lack of situational awareness, miscommunication, motivation, human-machine interfaces, etc. The cyber-physical systems view focuses on the analysis of control loops (feedback, feedforward, positive, and negative) and, especially, interrelated loops, as their very different forms of interactions may result in behaviours that are impossible to recognise by analysing the single components of the loops. Also, many behaviours cannot be analysed in terms of single loops which are ultimately influenced by other control loops.

While the division of the two views on engineering systems is meaningful for the identification of emergent hazards, deficiencies in control loops of organisations (as part of socio-technical systems) may also play a major role in triggering emergent failures in engineering systems. Taking the cyber-physical systems view does not deny accounting for the influence of the social dimension, as, for example, malicious influence on cyber-physical systems via cyber-environment and cyber-physical components as well as unintentional human errors may well be contributing factors to emergent hazards.

Emergent Hazards in Organisations

Starting with taking engineering systems as socio-technical systems one can focus on hazards due to their management and organisation. In more physical engineering systems such as refineries, water supply, and electrical power networks, it is unusual for management or the organisation to have a direct effect on control or to be able to cause accidents directly. However, they can cause accidents indirectly, either by giving inappropriate or erroneous instructions, or by failing to communicate necessary information, or by failing to supply needed resources, equipment, staff, or training. Managements and organisations can also cause severe incidents in systems which involve pure information processing, such as hospital administrations or electronic trading systems.

Many, and in some systems most, of the interactions involved in accidents take place between nominally unrelated organisational systems. An example was the Piper Alpha gas compression platform accident in the North Sea in which 185 people were killed (Cullen 1990). The accident involved failure of an operator to effectively communicate plant status information to another when coming off shift. The inoperable status of a compressor system was due to maintenance being incomplete. The system has not been made safe at the end of a shift. The unfinished status of the maintenance was not adequately transmitted. As a result, an unsafe compressor was started; natural gas escaped and exploded when ignited. The accident continued and was made much worse by operation of other platforms supplying gas to Piper Alpha, which continued to supply gas to the fire because they did not have authority to shut down production. All of these failures involved defects in the organisation and organisational practices.

In this accident, there were two breaches in communication, one between persons at the same level in the organisation, because there was no "overlap" for briefing at the end/beginning of a shift and no effective formal system to bridge the gap. The second breach was between two levels of hierarchy, since the decision to shut down could not be made by platform operations managers offshore, only by higher-level managers onshore, and these could not be reached. Also this involved the interaction of two separate hierarchies with different priorities and different situation understanding.

Analyses of major accidents in nuclear power industry, marine and air transport, and oil and chemical industries point to organisational and human problems as root causes. Reason (2000) has designated this "the age of the organisational accidents".

The SAM approach (Murphy and Pate-Cornell 1996) was an answer to "Reason's call for new risk assessment tools that can accommodate the organisational causes of accidents". The approach – a pioneer of this kind of analysis – was demonstrated for its performance on the Piper Alpha accident and some others (Pate-Cornell and Murphy 1996; Pate-Cornell 1993; Pate-Cornell and Fischbeck 1993). It proved an efficient tool for post-accident analyses and can be extended to provide a predictive approach to hazard identification (Pate-Cornell and Murphy 1996).

Failures in organisational systems have been analysed by Leveson and colleagues using the STPA method (Leveson 2011). This method considers systems as a hierarchy of control loops, extending functional failure analysis back from the physical systems through to administrative systems. This covers failures in hierarchical organisations, but there are many organisational structures which go beyond the hierarchical structure and which are much more complex as will be seen below.

Another organisational structure is that of cliques (Taylor 2020a), which are groups of people with extensive communication between them. Cliques can exist as background organisations acting in parallel to formal management hierarchies. Emergent behaviour in cliques is well documented in sociological literature (Tichy 1973). Some kinds of behaviour which can arise are:

- Trust and mutual knowledge of group member capabilities allowing the groups to react quickly and effectively to problems. This mutual dependence can result in enormously improved performance, but it also results in a tendency to exclusivity; this can in turn lead to poor communication for persons or groups outside the clique.
- Development of "group beliefs" which may or may not reflect reality (an example is disbelief in the importance of vaccination).

- Pursuit of clique goals which may or may not align with other organisation goals.
- Conformity, possibly leading to tunnel vision, suppression of initiative.
- Exclusion, leading to lack of communication.
- Rivalry.
- Cronyism.
- Mobbing.

An example of the adverse effects that can arise in cliques was the case of a person appointed to a post as team leader of a fire-fighting department in an oil terminal (personal observation). The person had achieved the post through the influence of the operations manager who was in the same religious group. When a fire did occur, the fire team leader could not deal with it. He called the operations manager, who left his post in order to support the fire team leader on site. This meant that he was unable to coordinate control and was unable to call on mutual aid. Fortunately, the fire was not large.

For predictive analysis, the hazards emerging from cliques are particularly difficult to identify, because it is hard even to identify the clique and even harder to determine the character of the clique.

The different organisational structures that can, and usually do, exist within the same organisation and the interactions between these can be particularly complex. Taylor (2020a), in a study of management and organisational errors in safety management systems in the oil, gas, and chemical industries, observed 162 organisational and managerial weaknesses which can lead to complex and in some cases emergent accident scenarios.

Some other mechanisms causing emergent behaviour in organisations are the following:

- Overload, lockout, deadlock, log-jam
- Procedural drift, organisational decay, changes in practices
- Myth generation and management by myth
- Management by solution of the most recent problem, not the next one
- Island sub-organisations, silo generation, personal kingdoms
- Overpromising and under-budgeting
- Staff turnover waves
- Lack of realistic feedback, working in a fog

All of these can occur without any real error at any point in time, but instead as the result of small variations in individual and subgroup behaviour which at the time seem reasonable or positive. One example is drift into failure through continuous pressure for “efficiency”.

Emergent Hazards Due to Malign Action

One of the most dynamic sources of hazards today is computer technology. This technology becomes an inevitable part of any engineering system, and there are several reasons for it to be a trigger of hazards. Computer programs and computer operation systems grow in complexity, and it is very likely that errors are present and stay latent until some point in the future when the confluence of multiple controlled conditions and input variables produce unwanted outputs that can in turn negatively influence control actions. These are undeliberate failures that can be (though only in principle) removed by a better debugging and/or incidental detection. However, as engineering systems are systems which are so tightly intertwined with and dependent on humans all the way through their design and decommissioning, deliberate introduction of failures and malicious acts are a reality. People (who are not supposed to) can now take control over engineering systems, change their functionality, harm other people, destroy assets, etc. while acting remotely thousands of kilometres from an attacked object and being extremely difficult to identify and bring to justice.

Malign efforts have been developing since the 1960s and are continuing:

- Phone phreaking (using fake signals to open especially international telephone connections) began in the 1960s as a way of avoiding call charges. Largely obsolete now due to the low cost of Internet chatting and online video communication, it is taken over by Van Eck phreaking, which is a form of eavesdropping that uses key press loggers, signal transmissions from keyboards, screens, and other peripherals to spy on electronic devices (Van Eck 1985).
- One of the first recorded security breaches from computer systems was from the CTSS multi-user computer system in 1965, due to accidental simultaneous access to a temporary file, making password control file visible for all.
- Illicit access via back doors, that is, forms of access deliberately left to allow programmers to modify or test software, and presenting security weaknesses have continued from the late 1960s to the present day.
- The possibility of computer viruses (programs which can take over the control of a computer, either openly or surreptitiously) was studied and discussed from the early 1970s and became a reality in 1982. Viruses became a widespread problem in gaming and hobby computers in the 1980s.
- In 1983, the possibility of "Trojan Horses" was reported. These have continued to be a problem, through the mechanism of "social engineering" (fraudulent access to a computer and direct installation of a Trojan) and "phishing" (inviting opening of access or initiating download by means of seemingly harmless or useful web pages).
- From 1987 onward "computer worms", which can spread from computer to computer, were noted in early networks and became widespread after the growing development of the Internet.
- In 1989, the first recorded instance or "ransomware" (taking over a computer network and encrypting or otherwise threatening valuable data) was recorded.
- An early "denial of service attack" (prevention or degradation of performance of a web site by submitting massive access traffic, often by co-opting innocent computers via a worm) occurred in 1997.

- Since 2000 there has been an increasing use of Internet connections in cyber fraud, market manipulation, cyber bullying, identity theft, cyber blackmail by threat of publication, election manipulation, and other malign uses.

This list is not exhaustive, and it is doubtful that any list ever could be. There are now large numbers of highly educated and highly self-educated individuals dedicating millions of person-hours to find and exploit weaknesses in our systems and large criminal organisations doing the same. There are also nation state security organisations both planning for cyber defence and cyber warfare and also engaging in surreptitious cyber warfare.

While most of malign efforts do not have influence on the safety of engineering systems, nevertheless, the same or similar activities can be recalled to trigger safety-related behaviours. Keeping this in mind, lessons learned from any successful cyber-attack should be remembered when designing engineering systems for safety.

To some extent, the problems of cyber criminality are self-inflicted. The majority of current attacks use techniques which are well-known and for which defences are also well-known. The field of security engineering is now well established. Nevertheless, there will be novel problems even for the best defended systems.

The worst aspect of security problems is the potential for widespread and catastrophic adverse effects. Just a few examples illustrate the potential:

- On 12 May 2017 a massive ransomware attack has shut down work at 16 hospitals across the United Kingdom. According to the Telegraph newspaper, the attack began at roughly 12:30PM local time, freezing systems and encrypting files. When employees tried to access the computers, they were presented with a demand for $300, a classic ransomware tactic. The attack cost the British National Health Service £92 million, not just in ransom, but also in lost “productivity”. The virus was a general worldwide attack, but the hospital case illustrates how malign software can affect human lives. If the virus had a longer-term impact, something which would be relatively simple to contrive, many life-saving functions would be interrupted.
- The Code Red worm was released on 13 July 2001. The largest group of infected computers was seen on 19 July 2001. On this day, the number of infected hosts reached 359,000. The malign effect of the virus was to launch denial of service attacks on several fixed IP addresses, including the IP address of the White House web server. Several other web page server viruses are known. The worst global effects arise from changes in server message packet routing policies, which can cause log jams in large sections of the Internet. Remembering that the Internet is now used for many control functions essential to lifelines such as power and water supply, the potential becomes obvious.
- Cyber-physical systems are those with a physical part, such as an oil refinery, a railway system, a wind turbine or an autonomous car, and an extensive computer system. They are an attractive target for malign acts, which is proven by historical record. The Stuxnet worm is one example. Stuxnet is a malicious computer worm (program which searches for and infects other susceptible computers), first

uncovered in 2010. Thought to have been in development since at least 2005, Stuxnet targets system control and data acquisition (SCADA) systems and is believed to be responsible for causing substantial damage to Iran's nuclear weapons program. A further attack on a cyber-physical system is the TRITON attack in Saudi Arabia in 2017. The attacker got access to the IT corporate network and further penetrated into the operational technology control network and took control over safety-instrumented systems attempting to deactivate it and cause the plant explosion. Fortunately, the disastrous scenario did not occur.

The various forms of malicious action, and their development over time with new and creative forms developing on almost a yearly basis, indicate that this will be a continuing source of emergent effects.

Emergent Hazards from New or Hitherto Unknown Accident Physics, Chemistry, and Biology

There are over 400 known physical phenomena that can result in accidents (Taylor 2012) and far more chemical effects such as various reaction types. New phenomena are found every year. These need to be regarded as emergent phenomena, but they can generally be dealt with during design if identified.

The lessons learned analysis (Taylor 2016) method was developed as a supplement to hazard and operability (HAZOP) analysis (Kletz 1999), in order to support identification of rare or unusual problems. It is very simple. As an analysis proceeds, a computer program is used to retrieve accident examples related to particular types of equipment, different substances, and different operations under study. These are displayed to support the analyst.

An example of a hitherto completely unknown problem is an accident from a natural gas drier (Taylor 2020b). This used zeolite (natural porous sorbent) to absorb water. Because the natural gas was very pure, it was not noticed that the zeolite could absorb hydrogen sulphide as well. No problems occurred for many years, but an accident happened eventually when labourers were changing the zeolite by shovelling it through a manhole into a skip. Unfortunately, during this work, a rainfall occurred, which was unusual in the desert environment. The water caused absorbed hydrogen sulphide to be released, and the toxic gas killed several workers. As far as is known, this is the only accident of this kind to have occurred anywhere, but it is remembered by the lessons learned database anyway.

There are some accidents which involve physical and chemical effects which cannot be explained or reproduced even now. Taylor (2020b) describes some of these. New materials, and new effects of materials, are discovered at a steady rate, and some of these introduce new hazards.

For instance, micro-particles of plastic (particle size from 100 nanometre to 5 mm) have been observed in the seas since 1979 and are now also detected in water supplies, soil, and air. The particles are now included in cosmetic products and clothing and are shed as debris from breakdown of clothing, packaging, and plastic products. It is known that plastic micro-particles can pass through cell walls. It is also known that plastic micro-particles can absorb carcinogens, toxins, and pathogens from the environment, including poly-aromatic hydrocarbons (Cox et al. 2019; Anderson et al. 2016). It is also known that plastic micro-particles can release hormone mimetic plasticisers (Browne et al. 2011). There has been little research to determine the importance of these effects.

The potential for adverse effects of genetic engineering is in principle enormous. Changes to viruses, for instance, may have huge global effects. In 2005 US CDC published results from the recreation of the 1918 Influenza Pandemic Virus. The purpose was to support development of anti-viral drugs. Between 1917 and 1920, over 50 million people died due to the influenza strain so that the risk level can be assumed to be high. The protection measures were among the highest ever used (Jordan et al. 2020).

The guidelines and safety level engineered measures for containment of genetically engineered organisms have proved over the years to be effective, with few failures. The main extensive failures have been in loss of containment for genetically modified crops, including some unapproved crops (Fulmer 2000). Since the modifications were intended to be benign, the consequences have largely been economic, with some recalls of products necessary. Threats from genetically modified food crops include that of transfer of disease and pest resistance from crops to weeds, inducing "super-resistance" (Service 2013).

As an example of possibly unexpected side effects, the development of bacteria which could decompose plastic waste has been attempted with some successes. The promise is the elimination of a large problem of plastic waste. The main threat is the rapid corrosion of plastic products, especially of cables and pipelines in the soil (Shosuke et al. 2016).

Hazardous Behaviours Arising in the Absence of Component Failures or Errors

Causes of emergent hazards in engineering systems can be situations in which no individual component failure occurs; however, the system still exhibits failure behaviour. A simple example is supply of hot water to a row of shower cubicles in a swimming bath or a (rather cheap) hotel (Fig. 1). The competition is for hot water. There are two fully interacting loops, and runaway (opening the shower valve to maximum hot) is a definite possibility in order for an individual to compensate for multiple demands on the hot water supply. This can lead to a serious consequence, possibly resulting in burns to the person affected, when one or more people stop using the shower.

Using traditional hazard identification approaches like HAZOP or failure mode, effect, and criticality analysis (FMECA) and analysing this system by looking into failure mechanisms of each component will not identify the mentioned hazard. It is only an understanding of the whole system and connections between its parts that will enable analysts to predict this hazard.

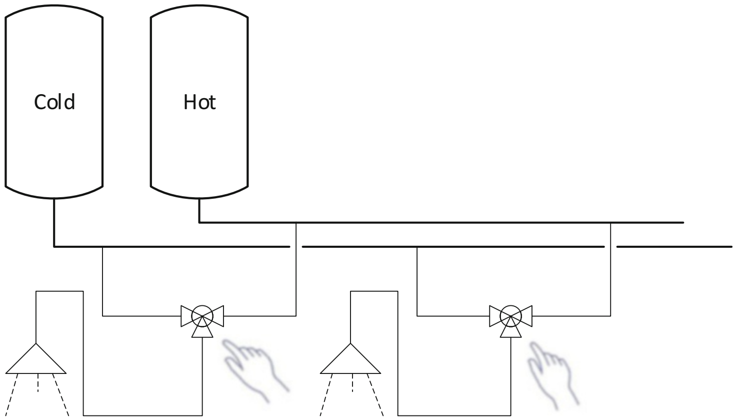


Fig. 1 Competition for hot water

One of the main problems of the design of large and complex systems is that they are complex, and prediction of all the problems, which could occur, becomes very difficult. Perrow (1999) introduced the concept of "normal accidents" to describe the problems arising through interactions between subsystems in large and complicated technological systems, largely those which arise through human action. His motivation for this was observation from specific accidents in nuclear power plants, but he found evidence from petrochemical plants, aircraft, marine accidents, dams, earthquakes, mines, space systems, weapons systems, and genetic engineering. His thesis was that modern systems have become so complex that they cannot be operated safely.

The term "normal accidents" is meant to signal that, "given the system characteristics, multiple and unexpected interactions of failures are inevitable". In spite of the name, individual types of these hazards are rare. They are important because there are so many possible types; their contribution to risk can be large and even dominant. This is certainly the case in modern aircraft safety and in air traffic control. For this reason, it is important to study them. Perrow (1999, p. 43) writes:

> "Nothing is perfect: every part of every system, industrial or not, is liable to failure. Common run-of-the-mill industrial plants have a steady run of unremarked failures. The more complicated, highly engineered plants, such as chemical, pharmaceutical, and some steel processing plants, are no exception. The more complicated or tightly coupled the plant the more attention is paid to reducing the occasion for failures, but [. . .] this can never be enough."

From the study of actual accidents, Perrow identified a number of interactions that can contribute to "normal accidents":

- Tight coupling
- Tight spacing
- Many common mode connections

- Personal operations specialisation and limited overview
- Unintended and unfamiliar feedback loops
- Limited understanding of processes
- Hasty decision-making or decision-making under time stress

When systems having any of these features are found also to involve significant potential accident consequences, then analysis is needed to ensure that at least the risk is minimised.

Sneak problems are another type of emergent hazards that "cause occurrence of unwanted functions or inhibit desired functions, assuming all components are functioning properly" (NASA 1995, para. 50.2.3.2). They are designed-in flaws and inadvertent modes of operation.

The concept of a sneak path was introduced by Rankin (1973) to explain the failure of the Mercury Redstone launch rocket in 1960, which occurred despite that there were no component failures. A circuit was established through an alarm lamp that caused a rocket fuel control valve to shut a few seconds into a launch, due to an earth cable being pulled away 29 msec before the control umbilicus.

Typically Sneak Circuit Analysis has been advocated by the defence and aerospace communities, and current standards and guidelines include NASA's Sneak Circuit Analysis Guideline for Electromechanical Systems (1995) and Boeings Sneak Circuit Analysis Handbook (Boeing 1970).

Sneak paths are emergent in that they can occur in systems in the absence of any component failure. They are properties of systems as a whole and can be classified into four basic types (Miller 1989):

- *Sneak paths* – unintended electrical (current) paths within a circuit and its external interfaces.
- *Sneak timing* – unexpected interruption or enabling of a signal due to switch circuit timing problems which may cause or prevent the activation or inhibition of a function at an unexpected time.
- *Sneak indications* – undesired activation or deactivation of an indicator which may cause an ambiguous or false display of system operating conditions.
- *Sneak labels* – incorrect or ambiguous labelling of a switch which may cause operator error through inappropriate control activation.

Sneak circuit analysis is a method which relies on identifying patterns in electronic circuits and investigating failure modes for the patterns rather than components. An alternative method was developed by Taylor (1994). This involves finding potential sources of signals or flows which can be hazardous, and finding targets for the flows, then searching for all possible paths which can connect source and target, including "unusual paths" such as via drains, earth connections, or manual transfer. Then "facilitating conditions" which allow the paths to be connected are identified. The method can be extended from electronics to process systems, hydraulic controls, pneumatic systems (Whetton 1992), software, and organisations. An example (Køge, Denmark 2006, personal observation, unpublished) was a strange epidemic, in which over 180 people were infected by 64 different diseases. The problem was traced to a water supply, and the suspected source was a wastewater treatment plant. The path for the transmission was traced to a hosepipe, illicitly connected to a wastewater filter to allow back washing. The facilitating conditions were the error of the operator, but also the failure of a check valve, and the simultaneous failure of two drinking water pumps which allowed water supply pressure to fall below the waste water filter pressure.

All of the examples demonstrate failure behaviours arising because of problems in the structure of the system, in some cases in the absence of component failure while in some other facilitated by component failure.

Side Effects and Unintended Consequences

One of the major problems with engineering decisions is that we design to achieve an objective. The systems we design generally have side effects that are not often recognised until they manifest themselves at later times. For example, we design power systems to supply power, but these have produced pollution. We therefore have designed pollution prevention systems, which require energy and reduce efficiency and therefore increase consumption of fossil fuels.

Side effects are not necessarily emergent phenomena but often emerging, as causal links can be traced – sometimes readily – to events that trigger them. Emerging phenomena or risks are those that are either new (not evidenced until now) or known as manifesting themselves in different setups rather than in the newly designed. They can be viewed as unintended consequences accompanying emergent phenomena, and it is difficult to predict their full range. Systematic methods for their identification simply do not exist.

The largest of these "hazards", by far, is the unintended disturbance of the climate as a result of our progress in industrialisation, fuelled by carbon-derived energy. There are other major problems of this kind that will be seen increasingly. Apart from global warming being an unintended consequence, climate systems involve very large number of physical feedback and feedforward loops which imply the possibilities for structural instabilities.

Modern communications systems, particularly Internet-based communication, give rise to a range of unintended adverse effects, among others:

- Telefonitis, dedication to large fractions of the day to telephone communication in a compulsive way
- Addiction to computer games or computer gambling
- Centralised gathering of personal information (not necessarily malign) and subsequent bias in its use such as for approving or declining insurance, approving or rejecting employment applications (malign effects not necessarily intentional)
- Publication of personal information by accident
- Deep fake communications, with real persons realistically but falsely portrayed
- Reduction in time available for physical and outdoor activities

The current developments in robotics and automation offer amazing wonderful opportunities for elimination of burdensome work, more precise production and surgical operations, and providing services for the infirm and handicapped. At the same time, automation and robotics have some adverse effects. One of them is gradual elimination of unskilled and semi-skilled jobs. As an example, it is only a matter of time before the job of check-out operator is eliminated or reduced to an absolute minimum, and robot “burger flippers” have already been tested. The job of bank teller has been largely eliminated by the ATM. Even the job of road-sweeper now requires training in operating road sweeping machines and provides only a fraction of the earlier employment opportunities. This may be regarded as a good thing in a society which lacks workpeople. But in a society where not all people can upgrade through higher education and training, and where the worth of a person in society is defined by their contribution via work, the developments of automation and robotics robs many of their self-respect. This may not seem to be a safety problem, but it has definitely led to societal unrest, at times violent. The path to unintended side effects can be long and may only become obvious over time.

One more example is that of the cashless society promoted by banks and electronics payments companies. The arguments for a cashless society are the increase in efficiency (handling cash is expensive when compared with credit and debit cards) and the end of many kinds of criminality. That this is feasible is shown by the fall in cash robberies with the de facto growth of cashless transactions. Kidnap and mugging threats involving ATMs have increased, but even this would become impossible in a truly cashless society. At the same time, however, money laundering, including money laundering through banks, has increased exponentially. It can be imagined that new schemes for such criminality will be invented.

Techniques to Identify Hazardous Behaviours in Systems

Traditional Methods and Their Weaknesses

Originally developed in the 1960s and 1970s, risk analysis is one of the most important tools in achieving safe design. Risk analysis when used for design purposes can be viewed as a process of identifying possible accident scenarios and evaluating or judging the frequency and severity of the consequences. Scenarios will typically be chains of events, starting with a component failure or an operator error, and passing through a number of events to a final event which is generally one involving significant damage or harm to persons or the environment. In most socio-technical systems, the scenarios involve latent hazards or failures at some stage along the chain of events, such as the latent failure of a safety system.

A majority of existing (traditional) hazard identification methods, such as the abovementioned HAZOP and FMECA (for a longer list see ISO 31010 (2009)), are good tools to identify hazards and hazard scenarios that propagate sequentially from a hazard trigger to a final event in the fashion as it is graphically described by the “Swiss Cheese” model (Fig. 2) (Reason 2000).

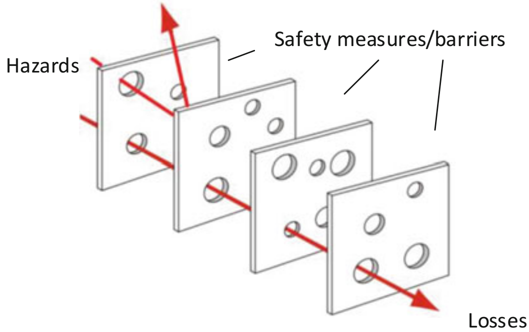


Fig. 2 Reason's Swiss Cheese model (Reason 2000)

Of more concern are complex systems where there are so many parts and so many interactions that it becomes very difficult to predict their performance. Unlike the sequential propagation of failures and disturbances, complex systems have groups of other interactions: knowledge, information, priorities, and side effects. Also there are many influences which affect the performance of functions generally, such as training, pressure to produce, cost saving, and simple poor practice. The form of "branching" interactions can have unlimited variations. Functionally unrelated activities can have interactions, for example, because of proximity or dependence on the same supplier. Interactions can arise, for example, due to activities being unfortunately timed to create sneak paths or resulting in oscillations and runaways. An example that actually led to an accident occurred in a chemical plant. One production unit required extra cooling water to control a chemical reaction. This reduced cooling water pressure in the common cooling water supply, leading to inadequate cooling in other production units. The other production units began to overheat and to also demand more cooling water. The result was an oscillating and continuing increase in demands from two of the systems, a runaway reaction and a reactor explosion (Taylor et al. 1982).

The number of potential interactions for any pair of components in two separate activities can become very large. If there are two parallel activities and each function pair has K forms of interaction, the number of potential interference cases is N^2K, where N is the number of components/functions. A Functional Failure Analysis, FMEA, or HAZOP type of approach to analysis such a system would be extremely cumbersome. However, a fault-tree-like approach has proved effective to establish causal links between causes and consequences.

In all, the traditional hazard identification and risk analysis techniques have enabled us to construct systems which would have been impossible before the 1960s. The Apollo missions to the Moon in the late 1960s were immensely complicated for the time (about seven million components involved in the rocket and vehicle system as a whole). By now the expertise to build such large systems exists not with any single person, but with organisations of hundreds or thousands of design engineers with different specialities and expertise.

Despite these advances there are still gaps in our abilities to analyse, predict, and prevent adverse consequences. Aircraft and trains still crash (as do cars, but for simpler reasons). Data processing systems fail, and some never even begin to work properly. Sometimes there are serious consequences of this. Financial systems fail regularly. Cars and medical devices are subject to recalls that on a world scale are relatively frequent (many per year). Widespread failure of power systems occur occasionally.

There are several gaps in traditional hazard identification and risk analysis methods:

- The methods were developed primarily for nuclear power plants, gas, and chemical plants, weapons systems, and aerospace systems which are designed as systems with well-defined interfaces between components. We cannot expect that the methods will work that efficiently for medical devices, cyber-physical systems, and organisational systems and others with flexible interactions.
- All of the methods are dependent on the knowledge of the analyst(s). Lack of knowledge about failure cause and consequence types is one of the most important causes of omissions in risk analyses (Taylor 2012). Most such omissions are rare events, but because they are not recognised, they do not receive attention and risk reduction effort. As a result, they are the largest contributor to residual risk for system types (Taylor 2020b).
- The traditional methods for hazard identification and risk analysis regard failures and errors as binary events; components either fail or do not fail; errors occur or do not occur. As pointed out by Hollnagel (2012), many accidents in real life result from the cumulative effect of small deviations from design intent. An action, for example, may be "slightly late", but too many such deviations may result in a needed action being "much too late".
- The methods do not work well for complex systems, especially those with many cross couplings and feedback loops.
- All of the traditional methods work in terms of individual component, individual "nodes" or individual functions. As we know, failures can occur in configurations of components without any failure in a specific component.
- The methods do not aim to identify the full spectrum of design error types. HAZOP identifies missing safety barriers, common cause analysis identifies design errors in general classes for redundant systems, and sneak analysis identifies errors which result in unwanted flow paths. There are many other design error types however. The main safety problem arising from design error is that it can introduce completely new failure modes, new system interactions, and new consequence types. An example is the so-called "pogo stick" oscillations which occurred in several of the early space launch vehicles, including the Saturn 5 launcher used in the Apollo project (Whiting 2018) and destroyed the Apollo 6 launcher.

Traditional hazard identification methods are virtually incapable in themselves of identifying possible emergent hazard problems, because their mode and cause lists are highly standardised, and are focused on components. Analysts may identify emergent hazards incidentally, by noticing new potential problems while examining system designs in detail.

Techniques to Capture Emergent Hazards in Engineering Systems

As demonstrated above, there are a number of system's features that cause emergent phenomena. However, in our view there are three that we can refer to as the key features and on which one should focus to attempt to predict emergent phenomena:

1. The organisation of parts in a system and the interactions between these parts that give the system its dynamical behaviour
2. Feedback loops that control a system's major dynamic behaviour
3. Sneak paths between concurrent processes and activities in a system that is assumed to be independent

As for the current state of the art, we can see three principally different methods that are capable of aiding identification of emergent hazards: one is to provide checklists of interaction types which are a-functional, that is, are not related to the designed interaction; another is representing a system in terms of feedback (possibly feedforward) control loops or a set of interacting control loops as described below; a third method is to represent a system in terms of sequential functionally unrelated processes (subsystems) (see Fig. 6 later in this chapter) that can in reality influence the performance of each other. In the latter case, concurrent activities can have sneak paths that are triggered by confluence of specific conditions, minor (possibly latent) failures, and parameter deviations.

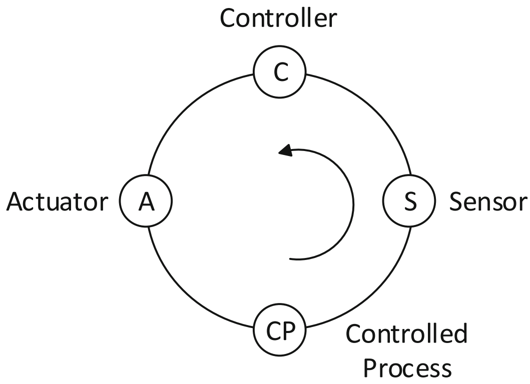
It is exactly the organisation of parts in a system (the first feature in the above list) that is the pre-requisite for emergent phenomena that can be identified by the methods. A control loop has a specific organisation of its components in a controlled process: sensor(s), controller, and actuator. This rather simple organisation can trigger such emergent behaviours as oscillation and resonance. An example is the Millennium Bridge in London that is briefly described below in this section.

Interrelated control loops can form a great variety in the organisation of their components that give rise to very different emergent phenomena. Some examples are provided below.

It is also the organisation of the parts that can give birth to emergent phenomena in functionally unrelated processes that are in reality give rise to interactions between the performance of these processes. Typical patterns in the organisation can in principle be identified that make different phenomena emerge. Rankin (1973) found a number of patterns in the connections of electrical components that can trigger emergent behaviours.

A simple control loop consists of four components, and its structure is shown in Fig. 3:

Fig. 3 A simple control loop



Leveson (2011) and Leveson and Thomas (2018) provide an extensive checklist of failure modes and deviations in the elements of the control loop that along with extraneous disturbances and unintended inputs can result in unwanted behaviours of the whole process. These can be complemented by a number of emergent failure modes arising in the feedback control as a whole. These are:

- Oscillation, hunting and resonance, surging
- Overshoot or undershoot and control inaccuracy
- Unwanted change of control mode, phase change in the controlled system
- Lag, hysteresis, backlash, stiction
- Intermittency, slow response
- Drift in parameter values
- Saturation and reaching the limits of control rangeability
- Wind up, bump transfer
- Poor turn down capability and instabilities arising when system throughput is reduced

Some of these phenomena are only relevant for electronic, mechanical, and process systems, while others can arise in socio-technical and cyber-physical systems. Some can occur in the organisational part, where feedback loops play a very important role. For the time being, there is no clear understanding of the full range of types of systems where emergent phenomena can arise, a situation that calls for continuing research to be able to predict them in the design phase. However, some cases have been found in organisations and described in Taylor (2020a).

A true socio-technical example of emergent behaviour of a system arose when the Millennium Bridge in London was opened to the public in 2000 (Atrogatz et al. 2005). The bridge was very light in construction and could sway (i.e., change the sideways position variable). As people walked along the bridge, it swayed. As it swayed, people staggered and adapted their gait to remain upright. This made the bridge sway even more because of resonance. Fortunately, it did not collapse and was closed for modifications for almost 2 years to eliminate the motion. It reopened in February 2002.

Another example is that of surge in a compressor of a gas turbine. Surge is a disruption of the airflow in the compressor that results from complex interactions of the piping system and compressor configuration. If the downstream pressure in the compressor rises due to, for example, blockage or a closed valve in the outlet piping, the speed of the rotor decreases because of resistance (internal physical feedback loop). Then, the flow of gas reduces, and the speed of the rotor grows again. As a result, the discharge pressure and rotor speed oscillate resulting in blades vibration and possible fatigue and rupture.

These emergent phenomena in control loops can in some cases be caused by component failure or error, but they can also occur in the absence of error or component failure. Instead, they can be inherent properties of loop design and of the physical systems. The problems can arise through perfectly normal changes in physical processes, such as delays arising in pipeline transport during cold weather. The problems can arise not only in hardware systems. They can occur in heavy and long queues of traffic, in which traffic jams can occur for no apparent reason other than slight and normal variations in driver behaviour. More dangerously, they can occur in mass evacuations.

More complex structures with connected feedback control loops are subsystems in which we can expect emergent behaviours taking place. In Fig. 4 we provide two examples of interacting control loops. The loops on the left hand side, (a), is one form of nested control loop. This form is used to override controls, such as supervisory overrides when a different mode of target system operation is required. It also represents systems with an ordinary operational control and an overriding emergency control. However, a lack of communication between the two controllers or a lack of situation awareness can result in competing commands, which in turn can cause an unwanted system behaviour.

Using the same sensor (Fig. 4b) to control a parameter for both normal and emergency operation can result in safety hazards if, for example, this is done in a building. Controlling the air quality by ventilation and using the same sensor(s) for

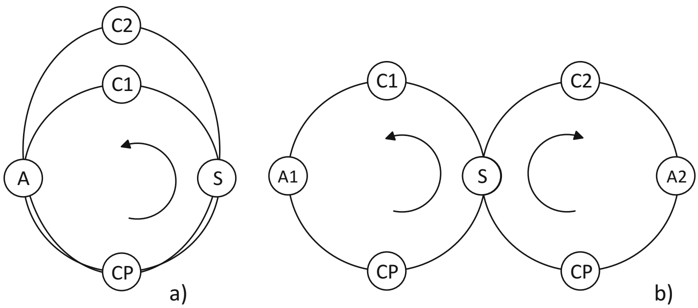


Fig. 4 Interacting feedback control loops: (**a**) nested loops, (**b**) loops using the same sensor as input to decision-making

alarming in case the concentration of CO_2 is too high (which occurs in case of fire) can stimulate the growth of fire. Eventually, the sensors can be damaged by the evolving fire, which may make the situation even worse.

For the simple example of hot water supply (Fig. 1), the two interacting feedback loops can cause a hazard possibly resulting in burns. A particular problem arises when one control loops stops competing with another, so that the supply of hot water to the second is increased. The structure of the two competing loops is shown in Fig. 5.

Identification of hazards in such systems can be made by simulations, but for hazards analysis the simulators need to be quite complex, taking into account possible failures and deviations of parameters from normal values. This means that the simulators themselves must be derived from a hazard identification.

It should be noted that emergent modes of failure in dependent control loops were first recognised in Leveson (2011), a prelude to the development of the STPA method.

The following is an example of four concurrent activities that appeared to be so interwoven that they resulted in a crash of two airplanes in which all occupants of both planes were killed. This accident took place on 19 November 1996 at Quincy, Illinois, and is known as Quincy runway disaster (NTSB 1997).

The United Express 5925 was flying in to land. The airport had no air traffic control and relied on mutual aircraft control. The pilot issued a request "Any traffic in the area?". There was no response. Independently, King Air 1127 was intending to take off on a training flight and transmitted "Taxiing out". UE 5925 announce "Inbound on [runway] 13". KA 1127 announced "King Air 1127 taxiing out, take off on runway 4". Visibility conditions were "Clear as day". KA 1127 in the cockpit reported to the trainer "Navigation set, radar set for takeoff". At this point, UE 5925 requested status and received a statement "Holding for takeoff", but this was not from King Air but another airplane (Cherokee) on the ground. The continuation "waiting behind King Air" was masked by noise. Notably, the message did not include the call sign (as indicated from UE 5925 cockpit voice recorder). It was concluded that there was a third aircraft, waiting in the queue for takeoff. UE 5925 crashed into KA 1127. All on board were killed.

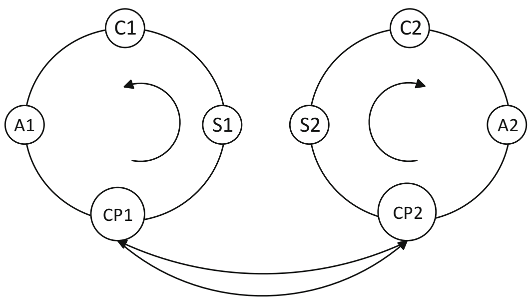


Fig. 5 Two interacting feedback control loops, as a model of the hot water supply

It was concluded that the King Air pilot did not check visually before taking off. There may have been an interference in visibility from the windscreen post.

The scenario of the accident is presented in Fig. 6. The example involve a primary sneak path and three "facilitating paths" which lead to the accident.

An accident of this kind is difficult to predict because it involves the study of four activities occurring in parallel. It is possible to predict the errors of the King Air pilot and even the causes (being under training and with an instructor focused on the training). Predicting the coincidental communications interference at just the wrong time and the failure of the Cherokee pilot to include his call sign in the communication leads to an almost incredible confluence of problems. The sequence probability would be regarded as extremely low, even if it were identified.

That such accidents happen, even though the scenario is very unlikely, arises because there are a very large number of potential alternative scenarios that would lead to accidents of this kind. The second aircraft could fail to respond because of intermittent radio failure; due to distraction; due to use of the wrong communications frequency; due to simultaneous communications; and others. The third aircraft could potentially confuse the situation in several other ways. Also, both aircraft could be unaware of their position.

The method summarised in the following section can in practice predict such accidents, provided that a large list of possible interference effects between activities is known. Systematic collection of lists of such causes has been carried out for process plant maintenance (Taylor 2020a) and for aircraft crashes.

Unwanted side effects can be straightforwardly analysed by cause consequence analysis (Taylor 2015) provided that the system model being analysed (piping and instrumentation diagram, electronic circuit diagram, system block diagram, etc.) is sufficiently rich. Simple functional models, by definition, will not allow unintended side effects to be found. Checklists of side effect types allow enhancement of models to be more encompassing.

Search for emergent behaviours in electronic devices and process industry can be carried out with sneak circuit analysis and sneak path analysis.

An actual case identified by sneak path analysis was that of a storage tank on top of a cyanide waste disposal building (Taylor 2020b). Any leak from the tank could allow acid flow to a drain and from the drain, via a tortuous path, to the cyanide waste, causing a hydrogen cyanide release. The accident was predicted, but occurred before prevention measures could be taken.

Avoiding and Eliminating Emergent Hazards

The most important step in avoiding or eliminating emergent hazards in engineering systems is to recognise that the problem exists and that it is important. In a study of 82 major accidents in the oil, gas, and chemical industries (Taylor 2020b), 16 were completely unpredictable by any current analysis method, and 28 were only after the fact predictable (i.e., predictable in future cases provided that lessons from the accident are remembered). Future predictability was primarily only by means of

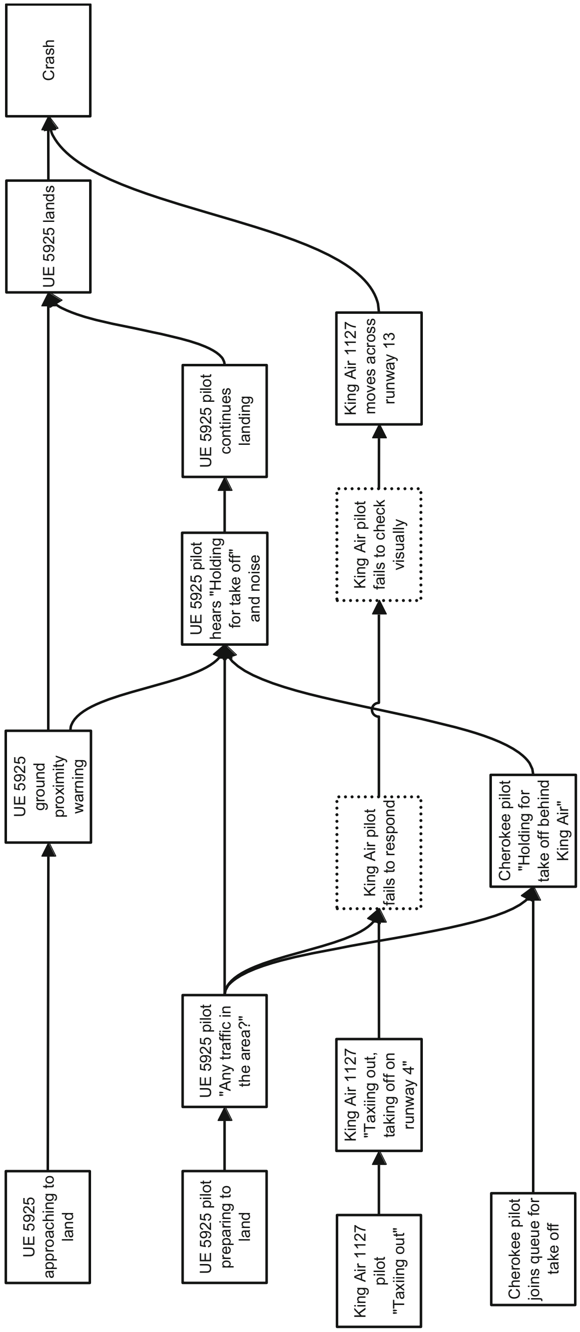


Fig. 6 Scenario of Quincy runway disaster. Broken lines indicate events which should have occurred but did not

lessons learned analysis. All of the plants had been subject to hazard and operability analysis and quantitative risk analysis.

Of the accidents that could be predicted after the event, a large fraction (36%) could be prevented in future by consistent use of lessons learned analysis. A further large fraction (16%) could be prevented by improved physical integrity audit and another fraction (16%) by consistent use of action error analysis (Taylor et al. 1982). The rest would require a range of more unusual methods: HAZOP as a part of management of change (Kletz 1999), Control HAZOP (CHAZOP) (Andow 1991), safety design review, deep HAZID, and piping safety review.

Accidents involving emergent effects in loop structures have proved to be rare in oil, gas, and chemical plants, presumably because these are designed with low coupling using buffering vessels between units. Accidents involving emergent effects in loop structures proved important in a study of aircraft accidents, over half involved failures in control loops, generally involving both pilot behaviour and equipment or other physical failure.

With the advent of cyber-physical systems, hazards arising in feedback control loops will become the main contributor to the risk profile of systems of this type. This is because the presence of control loops is one of the main characteristics of a cyber-physical system. In fact, even in simple cyber-physical systems, such as the control of the environment in a greenhouse, the number of feedback control loops (all of them dependent on each other) can amount to a dozen.

Identification of emergent hazards in loop structures can be carried out by extending hazard and operability and functional failure analysis methods, by recognising loop structures and applying checklists of typical loop failure modes. The method can be summarised as:

1. Describe the system to be analysed in terms of a functional block diagram or a system diagram such as and electrical circuit drawing.
2. Recognise the loop structures.
3. Analyse the loop structures component by component using the HAZOP checklist or the functional failure mode checklist.
4. Analyse each control loop and each interacting pair or group of control loops using an emergent hazards checklist.
5. For each failure mode or hazard, identify potential causes, consequences, and existing safeguards (safety barriers).
6. For each resulting accident scenario, identify the level of risk, and provide recommendations for risk reduction.

It should be noted that checklists for identifying emergent hazards in interrelated control loops cannot (to our best knowledge) be found in the literature.

Environmental and climate systems involve large numbers of interwoven feedback and feedforward loops too, many of which involve emergent phenomena (Young and Ribal 2019; Walsh 2014). Walsh (2014) writes:

"There are at least four factors that contribute to the polar amplification:

- A temperature feedback by which a warming surface leads to a more radiative loss to space in the warmer lower latitudes than in the colder polar regions;
- The albedo-temperature feedback associated with a reduction of sea ice and snow;
- Increased atmospheric humidity and the associated increase of down-welling longwave radiation; and
- Increased poleward transports by the ocean and atmosphere"

To these effects can be added a further feedforward loop. As waves break up ice, the Arctic Sea has more open water. This allows larger waves to develop and in turn to break up more ice. Effects such as this are emergent in two ways, firstly because many effects are more detailed than would be included in initial climate modelling and secondly because interacting feedback and feedforward effects are involved in an already complex tangle of feedback and feedforward loops.

Predictive analysis of emergent effects in complex interacting systems like the Quincy runway disaster (Fig. 6) requires first of all that the problem is recognised and amenable to analysis. The problems can then be identified by an extended version of standard analyses:

1. Describe the systems involved in the form of functional block diagrams, including a full range of system functions including maintenance and all operations groups. This is usually based on observation if the systems actually exist and is more difficult to do for systems being designed or planned.
2. Perform a sneak path analysis for each function, identifying paths and deviations along the paths which could lead to accidents.
3. Find the "facilitating conditions" along the sneak path which could allow the accident to occur.
4. Find interference paths from other functions which could enable the facilitating conditions.
5. Identify the deviations and happenstances in other functions which could cause or allow each interference.
6. Connect the emergent effects into complete accident scenarios.

It is quite possible to use the method to "predict" all accidents of types that have previously occurred and many more like them. It is also possible to predict accidents in complex systems which have not previously occurred, as shown by validation studies (Taylor 2012).

Security threats to computer systems are almost by definition emergent. Hackers strive to develop hitherto unknown methods of attack. Current methods for dealing with security threats are largely based on recording previous attacks and devising methods to detect the malicious programs. This is the basis of virus checkers which use "signatures" of known viruses and Trojans and search downloaded software or files such as spread sheets with embedded software, i.e., a lessons learned type of method. This led to the development of polymorphic and self-modifying viruses which could change their form. Such malicious software is detected by most modern virus checkers and fire walls, but still leaves us vulnerable to "zero day" viruses which utilise hitherto unrecognised weaknesses ("exploits") to stage attacks, usually coordinated ones. Defences from these increasingly depend on "white hat hackers" themselves searching for weaknesses and reporting them to software developers. This search is aided by an increasing use of open-source software, which is investigated by in some cases thousands of people concerned with quality and security assurance.

Many forms of attack, including future ones, can be prevented by simply blocking them. However, existing blocking techniques cannot be used where users deliberately load malicious software. This can occur by users accessing web sites which appear useful, but which are actually malevolent. It can occur by the use of external memory such as USB memory or external hard discs. And it can occur when an authorised user deliberately performs illicit loading of data or uses an auto-loading external device, either for criminal reasons or blackmailing or kidnapping of family. This can be blocked by eliminating all but specially authorised external memories.

Many of the serious security breaches today are in part self-inflicted, arising because users do not install software updates, leaving back doors open and exploits in place. An aspect of this is the repeated need for software updates, often to remove security weaknesses. Careful companies do not allow automatic updating. All updates are subjected to security testing in an isolated "sand box" before updating is allowed.

These predictive and blocking techniques are an inconvenience and can be costly, but are inevitably needed for secure systems.

In all, it appears that it will be possible to reduce the problems of emergent hazards due to lack of knowledge, or from newly arising accident phenomena, simply by ensuring that emergent hazards, after they are recognised, do not get repeated. This requires risk analysts to pay far more attention to accident case histories when carrying out hazard identification. It seems that it will also be possible to identify hazards arising in complex systems and activities. The main problem is that the emergent hazard methods produce a very large number of potential accident scenarios. There is therefore much work to be done in developing more effective methods for risk reduction. This applies equally to safety and security hazards.

Conclusions

The methods of risk analysis and risk-based design have served us well since the 1980s, when risk informed design approaches began to be used consistently in oil, gas chemical, and power plant design. The success was dependent though on systems being designed to be controllable, with a minimum of unintended interactions. This is illustrated, for example, by the failure of risk-based design in the case of the Fukushima Daiichi reactor in Japan, where all power supply sources failed at the same time due to coupling by flooding. Such interactions had been eliminated from the designs of many other nuclear reactors using risk informed engineering and careful attention to hazard identification.

There are many other engineering systems however where traditional risk analysis techniques fail. These are systems with complex interactions between subsystems, with tight coupling, and with forms of coupling which are not part of the engineer's concept repertoire. The range of problem types identified here are:

- System failures due to hitherto unknown physical, human, and social phenomena
- System failures due to intentional malicious actions
- System failures due to structural problems leading to unwanted interactions in systems
- Side effects and unintended consequences

These problems seem likely to increase as our systems become more complex, ubiquitous, and interlinked. Many or some of them cannot be predicted by examination of system's individual parts, as they emerge from the system without arising from any part of it alone, but because of interactions between parts.

In this chapter we provided a classification of the different types of emergent hazards in engineering systems and multiple examples supporting the division of these hazards into the four groups:

- Emergent hazards in organisations
- Emergent hazards due to malign action
- Emergent hazards from new or hitherto unknown accident physics, chemistry, and biology
- Hazardous behaviours arising in the absence of component failures or errors (structural emergent hazards)

Except for these four groups, we distinguish one more group that includes unintended side effects. These, in some cases, can be classified as emergent phenomena themselves and, in some cases, as emerging consequences accompanying emergent phenomena.

Traditional methods of hazard identification, such as hazard and operability analysis, FMEA, and fault tree analysis, are not, in their present form, suitable for identification of emergent hazards. The guidance for these types of analyses does not even recognise the problem. There are some methods which deal explicitly with emergent hazards, such as Rankin's pattern-based sneak circuit analysis, Taylor's sneak path analysis, and systematic lessons learned analysis. Methods such as STPA can be readily extended to identify other types of structural emergent hazards. In addition, new methods are introduced here, which have proved to be capable of identifying a range of structural emergent hazards. It has also been possible to devise methods which can reduce the occurrence or impact of emergent hazards.

In all, it can be seen that emergent hazards are an important group and become increasingly important as safety management techniques reduce the incidence of well-recognised hazards. In order to take emergent hazards into account, we need first to recognise that such hazards exist and that they are important. Once this has occurred, some methods are already available, but whether these cover all possibilities needs to be investigated.

Cross-References

- ▶ Designing for Human Behaviour in a Systemic World
- ▶ Dynamics and Emergence: Case Examples from Literature
- ▶ Ethics and Equity-Centred Perspectives in Engineering Systems Design
- ▶ Properties of Engineering Systems
- ▶ Risk, Uncertainty, and Ignorance in Engineering Systems Design
- ▶ Systems Thinking: Practical Insights on Systems-Led Design in Socio-Technical Engineering Systems
- ▶ Technical and Social Complexity

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Flexibility and Real Options in Engineering Systems Design

20

Michel-Alexandre Cardin, Ana Mijic, and Jennifer Whyte

Contents

M.-A. Cardin (✉)
Dyson School of Design Engineering, Imperial College London, London, UK

Centre for Systems Engineering and Innovation, Imperial College London, London, UK
e-mail: m.cardin@imperial.ac.uk

A. Mijic
Department of Civil and Environmental Engineering, Imperial College London, London, UK

Centre for Systems Engineering and Innovation, Imperial College London, London, UK
e-mail: ana.mijic@imperial.ac.uk

J. Whyte
Department of Civil and Environmental Engineering, Imperial College London, London, UK

Centre for Systems Engineering and Innovation, Imperial College London, London, UK

School of Project Management, The University of Sydney, Sydney, Australia
e-mail: Jennifer.Whyte@sydney.edu.au

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Abstract

Designing engineering systems for flexibility is of utmost importance for future generations of systems designers and operators. As a core system property, flexibility provides systems owners and operators with the ability to respond easily and cost-effectively to future changes. It contributes to improved economic value, sustainability, and resilience by enabling systems to adapt and reconfigure in the face of uncertainty in operations, markets, regulations, and technology. The field of flexibility in design has steadily evolved over the last two decades, emerging from the area of real options analysis, which focuses on quantifying the value of flexibility in large-scale, irreversible investment projects. Flexibility in design goes further by developing and evaluating novel design methods and computational procedures to enable flexibility as a systematic value enhancement mechanism in engineering systems. This chapter provides an overview of how the field has developed over time as well as design frameworks, computational methods, and algorithmic procedures to support such design activities in practice. It discusses important challenges and limitations with supporting case studies in aerospace, automotive, energy, real estate, transportation, and water management. The chapter highlights future directions for research, involving sustainability and resilience, data-driven real options, empirical studies and simulation games, machine learning, digital twin modelling, and 3D virtualization.

Keywords

Engineering systems · Engineering systems design · Flexibility in design · Real options · Risk management · Stochastic optimization · Uncertainty analysis

Introduction

Motivation

"First, we created a marvellous technological achievement. Then, we asked the question of how to make money on it" (MacCormack and Herman 2001). This quote from Iridium's former CEO serves as motivation for this chapter on flexibility and real options in engineering systems design. Iridium is a low earth orbit (LEO) satellite infrastructure deployed by Motorola in the 1990s to enable phone calls all over the planet. Back then, Motorola designed and deployed the system based on anticipation of a large user base of more than a million subscribers by the end of the decade. The system architecture and satellite design were based on a fixed constellation that would maximize coverage for the anticipated user base. In May 1997, the first five satellites were launched, and by September 1998, a 66-satellite constellation was launched and fully operational. The technology was functioning as designed and won several technology awards.

Unfortunately in the 1990s, land-based cell phone technology started to emerge, which reduced the demand for Iridium's services. Because all system capacity had been deployed, with satellites designed to remain in the same orbital configuration, nothing could be done to adapt and reduce the economic impact of this un-anticipated scenario. Iridium revenues did not grow fast enough to cover debt payments. In the early 2000s, the venture declared bankruptcy and was sold for less than 1% of the original US $4 billion investment (Hesseldahl 2001).

Iridium is an important case study for engineering system design because it highlights the need to consider uncertainty very carefully in early architecture and design activities, in order to prepare the system to deal with future changing operational conditions and risks. Uncertainty is difficult to account for in design, since prevalent on so many facets, including operating environment, economics, geo-politics, global health, etc. It requires designers to address important questions, such as the climate outlook in 10, 20, and 30 years and possible future regulatory standards, the timing and likelihood of the next global recession or pandemic, or how could the systems be attacked by cyber or physical terrorists. All such questions are obviously difficult to address and may even be uncomfortable for engineers used to deal with certainty and well-understood technologies.

There are typically two approaches to deal with uncertainty in engineering systems design. One approach relies on design robustness, which aims to provide the best performance despite wide variations in operational conditions (Jugulum and Frey 2007). This approach focuses on designing a system so it does not have to change or reconfigure to perform well under uncertainty. It involves methods such as Taguchi and other statistical design of experiment techniques (Taguchi 1987). Another approach relies on design for flexibility (de Neufville and Scholtes 2011). This approach promotes designing systems that are adaptable, changeable, and reconfigurable, in order to reduce impact from downside conditions and capture upside opportunities. This chapter focuses on the latter, discussing development of design frameworks, computational tools, and algorithmic processes to support the design of engineering systems for flexibility, as a way to improve expected performance under uncertainty.

Definitions

Flexibility in engineering design is an important paradigm to improve the expected economic performance and value of engineering systems (Cardin 2014). Many recent studies have shown that it improves expected performance by 10–30% – often more – as compared to standard engineering design methods, both in terms of economic and social value. For systems and mega-projects requiring large investments, in the order of $100–1000 million (or Euros, Sterling), the improvement potential can be significant. Flexibility "enables system owners and managers to respond easily and cost-effectively to changing circumstances" (de Neufville and Scholtes 2011). It is often referred to as a *real option*, providing the "right, but not the obligation, to change a system in the face of uncertainty". This technical (and almost legalistic) definition of real options is inspired from the financial options literature, from where the field has evolved. Real options analysis focuses on quantifying the value of flexibility in irreversible investment projects (Trigeorgis 1996).

This chapter exploits the notion of a *flexible systems design concept* to describe a design concept that provides an engineering system with the ability to adapt, change, and be reconfigured, if needed, in light of uncertainty realizations. It is different conceptually from a robust design concept, which makes systems functions more consistent and invariant to changes in the environment, manufacturing, deterioration, and customer use patterns – see Jugulum and Frey (2007). A flexible systems design concept is typically comprised of two components: (1) a strategy and (2) an enabler. The former is similar conceptually to the definition of a real option "on" a system by Wang and de Neufville (2005), also referred as a real option "type" by Mikaelian et al. (2011). It represents the aspect of the design concept that captures flexibility or how the system is designed to adapt to changing circumstances. Example strategies inspired from the real options literature include recognizing the ability to abandon a project that is doomed to fail, which helps reduce the impact from unexpected downside conditions, or deferring an investment until more favourable market conditions arise, leading to better upsides. Other examples include expanding production capacity or contracting it to accommodate fluctuating demand or prices, staging capacity deployment in smaller modular phases instead of all at once, switching between different types of inputs and outputs, investing in R&D to access more diverse cash flows in the future, or combining the above (Trigeorgis 1996). An important difference between a strategy and enabler is that an enabler – or *engineering option* (de Neufville et al. 2019) – requires deep engineering and technical knowledge about the system. An enabler is similar to the definition of a real option "in" a system by Wang and de Neufville (2005) or a "mechanism" by Mikaelian et al. (2011). It captures what needs to be done to the physical design and/or in terms of management to provide and use the flexibility in future operations. Enablers take a different form for each system, depending on the flexibility strategies selected and the uncertainty sources considered in the analysis.

Why Flexibility Matters

Flexibility in engineering systems design matters because it enables better value, both social and economic, by generating designs that improve the *distribution* of possible performance outcomes, as opposed to optimizing a design for a particular projection of the future. Flexibility takes the designer out of the comfort zone of designing for a particular future scenario. It uses uncertainty as a way to stimulate creativity and to consider other alternatives that would not normally be considered using standard design approaches. Figure 1 illustrates the typical impacts of

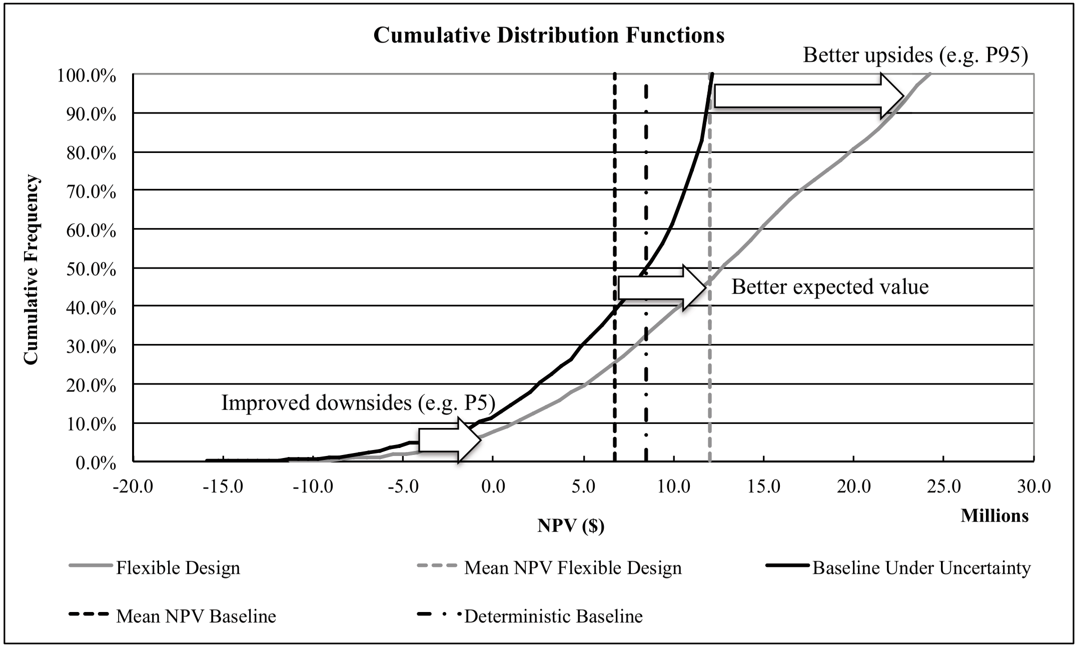

Fig. 1 Flexibility as an enabler of better value in engineering systems. (Republished with permission of the American Society of Mechanical Engineers, from "Enabling Flexibility in Engineering Systems: A Taxonomy of Procedures and a Design Framework, M.-A. Cardin, volume 136, 2014"; permission conveyed through Copyright Clearance Center, Inc.)

flexibility on systems value using hypothetical cumulative distribution functions, where net present value (NPV) is used as performance metric. Such distributions can also measure the system performance along other non-economic metrics, e.g., emissions produced and transportation time. Here NPV measures the total discounted profit that a system generates over its lifecycle; thus higher NPV is generally indicative of higher economic performance and value. On the figure, the dashed vertical line depicts the distribution for a system optimized under deterministic conditions. This latter approach assumes 100% probability of this one scenario occurring – which is unrealistic. In contrast, the two cumulative density functions illustrate the distribution of possible value outcomes for a particular design, subject to a range of probabilistic operating scenarios. The analysis recognizes that performance of a design can only be characterized probabilistically. Flexibility aims to reduce the impact of downside scenarios (captured by the lower end tail on the left), while also providing for better upside potential (higher end tail on the right) than a more rigid design. The net effect is to improve the expected (or mean) performance of the system by shifting its entire distribution toward better value outcomes.

Different flexibility strategies act differently on the probability distribution functions of design alternatives. Some strategies are better at reducing the impact from downside conditions (e.g., abandonment), and are therefore analogous to put options in the financial literature. Other strategies are best at improving upside potential (e.g., capacity expansion). Some strategies are more valuable than others and may have different costs. It is the designers' role to evaluate different strategies and combinations to find the ones that improve value as much as possible, and compare it to the costs of enabling flexibility in the system design (see section "Flexibility Costs" for further discussion).

There are many real-world examples of engineering systems that were designed for flexibility. The 25 de Abril Bridge connecting Lisbon to the municipality of Almada in Portugal is one such system. The bridge was originally designed to carry four car lanes, but engineers designed in the infrastructure the possibility to add more lanes in the future, as well as a railway on its lower platform, should usage and demographic patterns warrant it – an example of capacity expansion flexibility. This flexible design later allowed expansion to the current six car lanes and two-railroad tracks infrastructure that exist today. This design required a smaller initial investment than if full capacity had been deployed upfront, and deferred additional costs to the future, taking advantage of the time value of money by lowering their economic net present value. It also enabled more traffic between the two cities today, contributing to a growing economy several decades later.

Another example is the Health Care Services Corporation tower in Chicago, USA. While facing market uncertainty in the 1990s, the owner company designed the skyscraper carefully to accommodate 27 additional stories on top of an initial vertical development (Guma et al. 2009). The flexibility could be exercised only if there was a need for additional office space. In the 2000s, the company realized faster growth in personnel needs than expected. It decided to exercise the flexibility strategy to expand office capacity, and deployed the second phase, completed in the early 2010s. The strategy was carefully enabled in design by allowing for stronger structure and additional floors, enabling the company to deal proactively with market uncertainty at strategic times. Examples of flexibility exist in many other sectors, for instance, in car manufacturing, where companies design for standard components across different models and enable different elements of the design to be changed to produce different car variants (Suh et al. 2007) – an example of switching flexibility.

There are also a number of examples where systems were designed with too much rigidity or lack of flexibility. The Iridium system is one example. In the aftermath of the bankruptcy, a follow-up study showed that a flexible staged deployment strategy combined with satellites designed to change orbital configuration would have helped the system to cope better with changing market conditions, resulting in about 20% expected lifecycle cost savings (de Weck et al. 2004). The strategy involved deploying the constellation in phases instead of all at once to adapt gradually to rising demand, requiring the orbital configuration to change in space to accommodate growing coverage areas. This strategy would have led to a significantly different design than the one considered and actually launched by Iridium. It would have required designing each satellite to change orbit, thereby enabling the system to change the orbital configuration as demand and coverage evolved.

The IUT Global waste-to-energy system in Singapore is another example, surprisingly similar to the case of Iridium. The system was originally designed to convert large amounts of food waste into electricity, fertilizer, and biogas. The original design planned for a capacity to process up to 800 tons per day and power up to 10,000 homes. Launched in 2008, the system was ultimately shut down in early 2011 at a time where it was treating only120–130 tons per day, providing electricity to only 500 homes, and showing no signs of increasing needs for additional capacity (Lim and Ng 2011). Many examples of rigid systems exist in other sectors, such as Ghost Cities in China, where real estate developers (and government) planned for a particular future that did not materialize in terms of renting needs, wasting much time and valuable resources (Brown 2009; Cardin and Cherian 2017).

The examples above exemplify the need to consider uncertainty and flexibility more systematically in the design of engineering systems. The engineering discipline is becoming increasingly complex and is exposing our critical systems to significant threats from climate change, cyber or physical terrorism, and pandemics. This reality requires a fundamental shift in the way that system design activities are conducted. It requires new approaches that will enable future generations of engineers to create better value for society, and to better protect the environment (Whyte et al. 2020).

Background

From Options Theory to Real Options

Real options analysis emerged from the development of financial option theory. Financial options (e.g., calls, puts) provide the "right, but not the obligation, to buy (or sell) a stock at a pre-determined price". Note that this definition is very close to the one used above in the context of engineering systems design. In essence, financial options are instruments that provide flexibility to purchase (or sell) financial assets like stocks, crypto-currency, futures, etc. Their price quantifies the value given by the market to this flexibility. In the 1970s, the Black-Scholes formula was developed to quantify this value as a function of the spot price of the underlying asset S_t, time to maturity t (for a call, when the asset is purchased at the strike price), volatility of the underlying asset σ, strike price K (the price agreed upon to buy the underlying), and risk-free rate r_F (Black and Scholes 1973). The formula for the price of a call option C is shown in Eq. 1 (a slightly different structure exists for put options, and other exotic options). The structure of the Black-Scholes equation dictates that the cash flows of a call option can be replicated by buying a stock with borrowed money – assuming the right proportions, captured by the terms (d_1) and (d_2). The equation gives a good approximation of the price of the option, so long as a number of assumptions can be fulfilled. Example assumptions are that the portfolio (consisting of fractions of stocks and bonds) can be purchased in a frictionless market (e.g., no transaction cost or commissions) and at equilibrium between supply and demand (i.e., arbitrage enforced pricing). The idea is to find the corresponding parameters in the real options problem (e.g., volatility of the underlying, strike price), and assume that the value of the financial option corresponds to the value of the real option, provided the strategy is akin to the corresponding formulation of the Black-Scholes, i.e., the real option is similar to a call option, so one can justify using the form in Eq. 1:

$$C = N(d_1)S_t - N(d_2)Ke^{-r_F t} \tag{1}$$

where $d_1 = \frac{\ln\frac{S_t}{K} + \left(r_F + \frac{\sigma^2}{2}\right)t}{\sigma\sqrt{t}}$ and $d_2 = d_1 - \sigma\sqrt{t}$.

Cox et al. (1979) later proposed a simplified model to price financial options that converges to the Black-Scholes formula when $t \to 0$ (or equivalently the number of periods $n \to \infty$), exploiting binomial lattice and dynamic programming principles (Fig. 2). The idea is that a stochastic process (e.g., price) can be conceptualized as either moving up or down every time period, which helps simplify the computational problem. A backward induction process is then applied starting from the last period (or stage) using Bellman's recursive formula, enabling to value the option at time $t = 0$.

Toward the end of the 1970s, Myers (1977) suggested that options exist on real investment projects, thus coining the term *real options*. An example of real option is land, akin to a call option. Buying a piece of land gives the owner the "right, but not the obligation, to build a house or building", which will in turn generate income as rents and capital gains, in analogy to a stock paying out dividends and gaining capital value. Because of this analogy between real and financial options, the Black-Scholes and binomial lattice approaches, combined with simulations, became predominant to quantify the value of flexibility in real investment projects (Copeland and Antikarov 2003). Engel and Reich (2015), for example, used such technique to evaluate architecture options in many relevant industries.

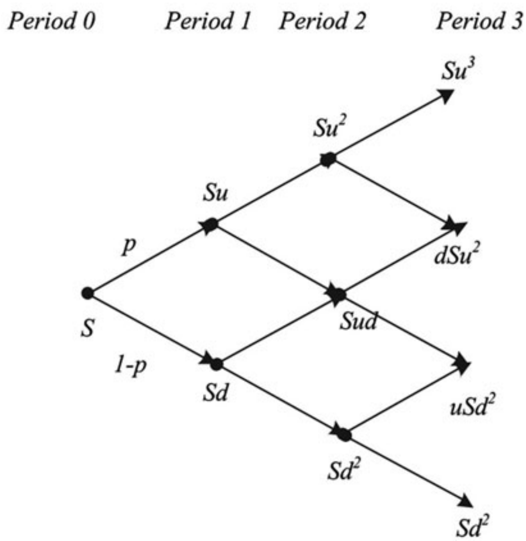

Fig. 2 Example binomial lattice as proposed by Cox et al. (1979) to value financial options. (Reprinted from Transportation Research Part E: Logistics and Transportation Review, Vol. 107, S. Zhang and M.-A. Cardin, Flexibility and Real Options Analysis in Emergency Medical Services Systems Using Decision Rules and Multi-Stage Stochastic Programming, pp. 120–140, 2017, with permission from Elsevier)

From Real Options to Flexibility in Design

With the development of real options came the need to develop methods and procedures to better support the design process to enable flexibility in engineering systems design. The field of *flexibility in design* emerged in most parts from a real options approach to flexibility analysis. Flexibility as a design concept, however, is not new and has been studied for a long time, for example, in manufacturing and product development (Sethi and Sethi 1990; Linsey et al. 2005). In contrast, the study of flexibility in the broader context of engineering systems design emerged in the early 2000s. An important distinction between the fields of real options and flexibility in design is that the former focuses on quantifying the value of flexibility – effectively aiming to price the real options – while the latter focuses on methods and procedures to embed flexibility in engineering systems design, as a systematic value-enhancing mechanism. Flexibility relies on value quantification in a similar fashion as done in real options theory, but more as a mechanism to rank order the possible design alternatives to support the design decision-making process (perhaps to a lesser extent to find the right "price" for the real options). In other words, most of the research in this field aims to extract important lessons from real options and engineering design theories, and then adapt or develop new methods to make those ideas more suitable for engineering design practice.

State of the Art

Design Frameworks

The point of a design framework is to provide engineers with a systematic approach to a given design problem. Many academics have proposed systematic frameworks to design flexible engineering systems (Nilchiani and Hastings 2007; Mikaelian et al. 2011), along with literature reviews to organize the research in the field (Ferguson et al. 2007; Saleh et al. 2008). The frameworks vary in form and substance (e.g., stepwise or flow process, different number of steps and activity types), but they generally involve the following phases synthesized by Cardin (2014) (see Fig. 3): (1) baseline design, (2) uncertainty recognition, (3) concept generation, (4) design space exploration, and (5) process management. Designing for flexibility rarely starts from scratch and usually evolves from an existing design referred as baseline. The arrows capture the fact that the process is not linear, but rather may circle around the different phases, going back and forth as needed, until valuable designs are identified and selected in early conceptual activities.

In Phase 1, designers generate one (or several) design that will serve as baseline, in order to compare the value generated by the flexible design alternatives in subsequent phases. This phase recognizes that, to design a flexible engineering system, one does not need to reinvent the wheel, so the process may start from existing expertise and past design experience with the system. This phase is

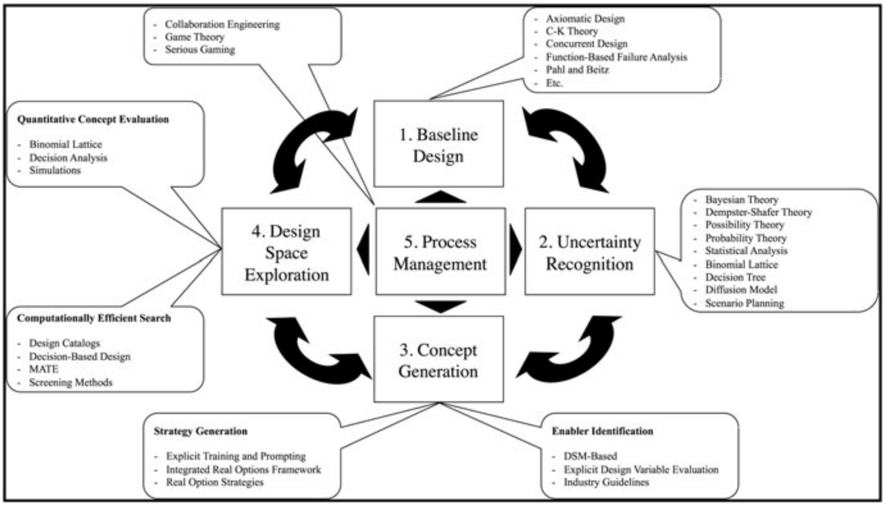

Fig. 3 Design framework for flexibility in engineering systems design, along with proposed procedures to support design activities in each phase. (Republished with permission of the American Society of Mechanical Engineers, from “Enabling Flexibility in Engineering Systems: A Taxonomy of Procedures and a Design Framework, M.-A. Cardin, volume 136, 2014”; permission conveyed through Copyright Clearance Center, Inc.)

important to quantify the benefits from flexibility later on, as compared to the cost of enabling it in the design. In Phase 2, designers consider the various uncertainty sources that may affect the system performance. This step is crucial, as it will help define and narrow down the types of flexibility strategies and enablers considered in subsequent steps. In Phase 3, flexible system design concepts are generated to deal with the main uncertainty drivers in Phase 2, considering the baseline designs generated in Phase 1, relying on creativity and other techniques (e.g., Design Structure Matrix). In Phase 4, the design space is explored systematically, essentially looking for the best configurations of the flexible systems design concepts generated in Phase 3, while explicitly modelling the uncertainty sources from Phase 2. Phase 5 captures the interconnections between all four phases and multi-stakeholder interactions needed to support the conceptual design activities. This is because flexibility rarely relies on the knowledge of one group of stakeholders (e.g., engineers). It requires inputs from other parts of an organization (e.g., executive management, marketing, sales) to provide information on the socio-technical context in which the system is called to evolve.

Iridium Example

The purpose of the design framework above is to support the design process for flexibility. This section illustrates how the framework could be used to revisit and improve (in hindsight) the conceptual design process for Iridium, building upon the analysis and solution proposed by de Weck et al. (2004) and design tools available in each phase (see circles in Fig. 3 and further descriptions below). In Phase 1, a standard design is considered for low earth orbit satellites. A baseline concept proposed by de Weck et al. (2004) is considered, consisting of 50 satellites operating along 5 circular polar orbits, at an altitude of 800 km and elevation angle of 5°, with communication capacity for 80,713 duplex channels. Assuming a 10-year lifecycle, 10% discount rate, three million users, and average monthly activity of 125 minute/month, the authors estimated the expected lifecycle cost of such design at \$2.01 billion, close to the actual development cost for Iridium (MacCormack and Herman 2001). In Phase 2, user demand is identified as the main uncertainty driver and modelled as a geometric Brownian motion diffusion process. In Phase 3, a phased deployment strategy is recognized as best to adapt to uncertain – but assumed growing – user demand. The system must be designed with smaller initial capacity, and enable flexible deployment of more satellites over time. To do this, the constellation must be designed to reconfigure in space to accommodate new user demand patterns and geographical coverage, as uncertain demand is realized, and more satellites are added. The design of individual satellites must cater for this strategy, and this is where the solutions starts departing from the actual Iridum system. In Phase 4, a lifecycle cost model is developed to quantify the performance of different design and deployment alternatives. To evaluate a large number of possible design configurations and expansion strategies, de Weck et al. (2004) conducted a tradespace analysis, similar to the one proposed by Ross et al. (2004). They found that the optimal initial design would require 28 satellites distributed over 4 orbital planes, at an altitude of 1,600 km, and 5° elevation, converging over time toward a

364-satellite constellation over 14 orbital planes, 800 km altitude, and 35° elevation. The analysis produces a radically different design solution than the baseline, which the authors show to reduce expected lifecycle cost from $2.01 billion to $1.46 billion, a 27% improvement. The savings arise from the ability to reduce exposure to downside risks, by requiring a lower initial capital investment, in case demand does not grow as anticipated. It also positions the system to capture more upside potential, should demand grow faster than expected. The strategy helps deferring satellite deployment until sufficient demand is realized to require more capacity, thus making a more sustainable use of limited material and financial resources (i.e., reducing the likelihood of unused capacity). This, in turn, contributes to reducing further the expected net present value of costs. For Phase 5, a setting that is most conducive of a productive design process in phases 1–4 should be considered. Ideally, such setting should bring together the key stakeholders and experts to cover various facets of the problem, e.g., engineering, financials, markets, and senior decision-making. ESA's Concurrent Design Facility or NASA's Integrated Design Center are example facilities promoting productive conceptual design activities. The facilities should enable teams of experts from different disciplines to work closely together on highly complex problems and improve overall efficiency of system design activities (European Space Agency 2021; National Aeronautics and Space Administration 2021).

Design Procedures

In Fig. 3, example design procedures are listed in the circles to support the design activities involved in each phase. The procedures in Phases 1–2 are well known and researched, e.g., Pahl et al. (2007), scenario planning, etc. The latest developments in the field have occurred in Phases 3–5, leading to a significant number of novel design methods and computational procedures, most of them thoroughly evaluated through empirical and case studies in various sectors. For example in Phase 3, as part of the integrated real options framework, Mikaelian et al. (2011) proposed a systematic approach to stimulate creativity and generate flexible strategies in UAV systems, by nudging designers to think explicitly about possible combinations of real option types (i.e., strategies) and mechanisms (i.e., enablers) ahead of the detailed design phases. Bartolomei et al. (2012) proposed the engineering system matrix, a holistic variant of a design structure matrix that represents the system-level dependencies within socio-technical systems. Their approach can be complemented by change propagation analysis (Suh et al. 2007) to identify flexibility enablers systematically, by looking at the ripple effects of changing design elements on to other design elements throughout the system, and identifying change multipliers as design components that are good candidates for flexibility – since those generate more change if unchanged, so worthwhile making more adaptable. Broniatowski (2017) compared system decomposition and layered designs as approaches to embed flexibility in design. Allaverdi and Browning (2020) proposed a new approach exploiting related principles to identify opportunities for flexibility in large-scale systems.

Many researchers also considered methods to design systems and products that exploit "ilities" related to flexibility, such as evolvability, pliability, and survivability (Luo 2015; Mekdeci et al. 2015; Richards et al. 2008; Patou and Maier 2017; Patou et al. 2016).

Phase 4 is the most demanding from a computational standpoint and warrants further details. Here, designers' focus is twofold: (1) developing models to quantify the benefits of flexibility and value added, using economic (e.g., net present value) and/or non-financial metrics (e.g., emissions levels, average route duration in subway systems), and (2) finding the recommended design configurations using advanced optimization and statistical methods. In terms of value quantification, standard valuation methods typically include decision analysis, binomial lattice analysis, and Monte Carlo simulations. The expected value of flexibility is quantified as the difference between the expected payoffs from the best (or stochastically optimal) baseline design(s) and flexible design(s). Decision analysis relies on decision trees and a backward induction process as used in dynamic programming (Bellman 1952). Starting at the final stage, the decision maximizing expected lifecycle performance is made at each decision point going backward in time. The folding back process goes backward until the initial stage is reached, where the overall expected lifecycle performance of the system is calculated. The decisions available at each stage represent how the system can adapt. For example, in Babajide et al. (2009), a flexible oil platform was carefully designed with additional subsea tieback connection slots to expand oil production capacity, while a rigid system could not. When oil reserves were found higher than expected, the sequence of decisions would reflect the ability to expand production (and revenues) as compared to a rigid design, affecting terminal payoffs. Binomial lattice analysis is similar to decision analysis, with the exception that in each stage the uncertainty can either go up or down relative to the previous state (see Fig. 2). To reduce the number of possible outcomes, path independence is assumed, and lattice nodes are allowed to recombine. A process similar to dynamic programming is applied to quantify the value of flexibility. de Neufville (2008) used this approach to value the flexibility to abandon a mine pit project subject to copper price uncertainty.

Under a simulation approach, a large number of uncertainty scenarios (e.g., price, demand) are generated using stochastic techniques such as geometric Brownian motion, mean reversion, or jump models. The idea is to emulate the system's behaviour under each individual scenario, measure the performance or value, and then collect meaningful statistics on the distribution of performance outcomes. This is best done using *decision rules*, which are akin to sign posts, or triggering conditions that must be met for the system to adapt to changing conditions. Decision rules emulate the decision-making process in operations in an intuitive manner, similar to an IF-THEN-ELSE statement, e.g., IF *demand reaches a certain level*, THEN *expand capacity*, ELSE *do nothing*. They combine both physical design elements (e.g., amount of capacity to expand) and managerial aspects (e.g., which threshold level to consider for expansion) in succinct statements, and can be optimized using simple spreadsheets, or more advanced methods like multi-objective simulation optimization, stochastic programming, or robust optimization

(Cardin et al. 2015b, 2017b; Caunhye and Cardin 2017). While the example above is simple, an important benefit of a decision rules approach is to enable analysis of more complex multi-variable design problems and uncertainty sources. Such approach is also well suited for a deep reinforcement learning formulation – see section "Future Directions". Figure 1 provides an example generic output from a simulation using decision rules, comparing the performance of different system design alternatives. Measuring statistics like mean performance, value at risk (e.g., fifth percentile), value at gain (e.g., 95th percentile), and standard deviation gives decision-makers a good idea of the performance, for different risk profiles. For example, a risk-neutral decision-maker may be interested in design solutions maximizing mean performance, since it balances downside risk mitigation and upside potential. Similarly, a risk-averse (seeking) decision-maker might prefer maximizing worst (best) case scenarios, thus focusing on value at risk (gain). The approach provides decision-makers with a range of solutions to select from, based on their risk tolerance profile.

Simulation models often lead to significant computational and mathematical challenges due mostly to the large number of possible uncertainty scenarios, metrics, design, and decision rule variables. Computationally efficient methods are needed to identify the best flexible systems design concepts, while dealing with the possible computational overhead. For instance, the Multi-Attribute Tradespace Exploration (MATE) framework proposed by Ross et al. (2004) explores the design space based on the configurations providing highest perceived value, based on decision-makers' utility attributes and costs. A Pareto set characterizes the designs of highest utility for each possible cost value. This tradespace captures transitions from one design state to another, exploring design alternatives via the concept of filtered out degrees, i.e., a design changing from a previous state, acceptable to a decision-maker based on development time and/or cost. Screening methods are also effective statistical approaches to reduce the number of samples needed to replicate the objective performance function. Such methods construct rapidly a simplified function or model and then identify best configurations using optimization methods – at the cost of sacrificing global optimality. Three general approaches exist and have been applied to analyse flexibility: bottom-up approaches use simplified versions of a complex, detailed design model (Lin et al. 2013), simulators use statistical techniques (e.g., response surface methodology) and/or fundamental principles to mimic the system's response (Yang 2009), and top-down methods use representations of major relationships between the parts of the system to understand system responses, as in systems dynamics (Sterman 2000).

Phase 5 addresses the social and collaborative setting under which flexibility can be generated in early design activities. It includes considerations of institutional and inter-organizational aspects in important projects involving multiple stakeholders. Phase 5 proposes and explores tools and procedures to either (1) provide a setting under which practical design activities in Phases 1–4 can be conducted, and for managing flexibility in real-world projects, or (2) provide an environment to better understand the conditions under which design activities are conducted through research. It includes methodologies to reduce barriers to implementation, to stimulate creativity, and to study agency problems and information asymmetries affecting the value of flexibility. For example, Phase 5 may be embedded in the design process through approaches like concurrent engineering (Kusiak 1992), to exploit task parallelization and new developments and technology to improve efficiency of collaborative design activities. Different governance structures can be set and explored to address the collective action problem arising from inter-organizational developments in projects exploiting flexibility (Gil et al. 2015). In terms of supporting research, game theory can be used to shed light on how different asymmetries affect the value of flexibility in major infrastructure system projects involving different stakeholders (Smit and Trigeorgis 2009; Smit 2001; Ferreira et al. 2009). The research can be complemented with empirical approaches like serious gaming – or simulation games – defined as "experience-focused, experimental, rule-based, interactive environments where participants learn by taking actions and by experiencing their effects through feedback mechanisms that are deliberately built into and around the game" (Ligtvoet and Herder 2012). Several researchers have relied on gamification to investigate the best methods to support the design and management of flexibility in engineering systems and projects (Cardin et al. 2015a; Gil et al. 2015).

Example Studies

The work on flexibility and real options spans a wide range of industry sectors and applications. Over recent years, a growing number of academics have studied flexibility in design in sectors such as aerospace, automotive, energy, real estate, transportation, and water systems (Silver and de Weck 2007; Chen et al. 2020; Koh et al. 2013; Sapol and Szajnfarber 2020; Kang et al. 2018; Strbac et al. 2020; Nie et al. 2017; Ma et al. 2017; Cardin et al. 2017a, c; Melese et al. 2015, 2017; Buurman and Babovic 2016; Esders et al. 2016; Geltner and de Neufville 2018; Gil and Tether 2011; Lethanh and Adey 2015; Hino and Hall 2017; Zhang and Babovic 2012). Many studies look into development and evaluation of new procedures to support the design process, with real-world demonstration applications. These witness the growing health and rising opportunities in this emerging and exciting field. This sub-section provides an overview of the work done, or in progress.

In the aerospace sector, Silver and de Weck (2007) proposed a time-expanded decision network to quantify the value of flexibility in design of heavy lift launch vehicles for space exploration. More recently, Chen et al. (2020) proposed a flexibility management framework for space logistic missions, using decision rules and multi-stage stochastic programming. In the automotive industry, Koh et al. (2013) proposed a process to assess levels of changeability (akin to flexibility), using dependency structure matrix, and a probabilistic approach to monitor change propagation, with demonstration in heavy diesel engine design. Sapol and Szajnfarber (2020) looked into the impact of implementation delays in exercising real options in military vehicle design and operations. Kang et al. (2018) proposed an optimization framework to redesign and invest in future vehicles, considering uncertainty in gas price, and emission regulatory standards. For energy systems, Strbac et al. (2020) looked into the role of flexibility and options for better decarbonization of the electricity system. Nie et al. (2017) used a real options approach to analyse flexibility in design and operations of transportation and storage network infrastructures for carbon capture and storage. Along these lines, Ma et al. (2017) studied flexibility in installation and operations of carbon capture and storage facilities using catalytic membrane reactors for hydrogen production. Cardin et al. (2017c) considered flexibility and real options in deployment of new nuclear power plants using a decision rules approach and multi-stage stochastic programming, considering social acceptance as an important uncertainty driver, along with growing demand in emerging countries. Melese et al. (2015, 2017) looked into the concept of flexibility in design and operations of infrastructure networks, such as pipeline-based carbon capture and storage systems. Buurman and Babovic (2016) integrated adaptation pathways, adaptive policy-making, and real options thinking to evaluate new climate change mitigation strategies. In the sector of building and real estate, Esders et al. (2016) looked at the benefits and drawbacks of real options thinking in work programs for building systems. Geltner and de Neufville (2018) proposed a practical "engineering" approach to value real options and flexibility in real estate development, based on a decision rule and simulation approach. In transportation, Gil and Tether (2011) looked into the interplays between flexibility in design and risk management in the context of London Heathrow's Terminal 5 infrastructure project. Lethanh and Adey (2015) considered the impact of real options thinking on design and operations of railway infrastructure systems. Cardin et al. (2017a) considered the value of flexibility in deployment and operations of car sharing systems under user demand uncertainty. For water systems, Hino and Hall (2017) considered real options as adaptation strategies to deal with flood risks. Zhang and Babovic (2012) considered a real options approach to architecture and design innovative water systems under uncertainty.

Challenges and Limitations

Enabling Flexibility

Enabling flexibility in engineering systems is a difficult process. Every system is different, faces different uncertainty sources and risks, and must fulfill different missions and purposes. Despite much ongoing research to develop frameworks and procedures, there is currently no "cookie-cutter" solution applying to all engineering systems. The frameworks and design tools above must be carefully applied to suit the needs of each intervention. The emphasis above is heavily geared toward engineering; however other important socio-technical aspects must be considered. Enabling flexibility is not always just about planning for stronger or shared infrastructures or being able to switch between different technologies. It may also involve setting up the right financial incentives in a contractual agreement or making sure that all stakeholders are agreeable to the flexibility being exercised at some point in the future. This relates to institutional and organizational considerations for embedding flexibility. Different organizations may have conflicting objectives regarding large-scale investments, especially in mega-projects like new airport terminals or railways, which may make it difficult to embed flexibility. Some investors might feel uneasy with the concept of flexibility, raise concerns about not deploying all the capacity upfront, for example, or may require a different capital structure to fund the venture. In real estate, neighbouring buildings may need to be notified of the possibility of a vertical expansion sometime in the future, which may alter their views of the horizon, and the building value. As a whole, flexibility must be considered not just from an engineering standpoint but also from other institutional, organizational, legal, and financial perspectives. Gil et al. (2015) investigated these issues and proposed various methods to deal with such inter-organizational challenges.

Flexibility Costs

Flexibility sometimes requires an additional cost upfront in terms of design, so that it can be used when the system is launched in operations. Without this, the system will not be able to adapt or change in light of operational uncertainties. To use once more Iridium as example, even if the company had wanted to deploy the system more flexibly in stages, it would have required designing the satellites to change orbital configuration, which is different from the way the actual system was designed. In other words, flexibility may have a cost, which is analogous to the premium paid to buy financial options. In the context of engineering systems, the cost may vary significantly depending on the system, strategy, environment, regulations, technology, etc. It is the designer's role to determine the most valuable flexible system design concepts, in view of the possible upfront cost. This upfront cost introduces a risk, of course, just like paying a premium for an option, and never exercising it. It is possible that flexibility will be embedded in the system and never used in operations. Perhaps the system did not encounter any conditions requiring adaptation or change, or perhaps the system capacity was good enough to enable good performance despite varying operational conditions – as in robust design. Recalling a definition of flexibility as providing the "right, but not the obligation, to change a system in the face of uncertainty", it is possible that the option will not be exercised at any point in time. The price paid is arguably lower than the expected value brought by the flexibility, and this value would not be quantifiable unless the procedures and methods described above were used. The premium involved is analogous to an insurance policy. The system operator or owner pays a price upfront to obtain a right, with the possibility that it will never be used. An individual paying a premium for a life insurance would not blame the insurance company for not dying! The idea is similar in the context of flexibility: it is a paradigm to manage risks and uncertainty in the context of engineering systems design, with the goal of improving expected value and performance in the long term.

Keeping Your (Real) Options Alive

Another issue is that a flexibility strategy that focuses on long-term performance improvement suffers the risk of being forgotten. Engineering systems are typically long lived, which means there is a high chance that the original designers, operators, and owners will not be the same individuals or group as those taking on operations in the future. This may create challenges and obstacles to “keep the (real) options alive”. For instance, there is a case where ownership of an infrastructure changed after several years, and the new system owner did not know about the flexibility embedded in the design by the previous owner. So, the flexibility was never used. This is why it is important to document and maintain the system’s capabilities carefully within an organization; otherwise it may very well be lost.

Too Much Flexibility

The goal of analysing engineering systems for flexibility is to identify the most valuable flexible system design concepts. It is not to make an engineering system flexible no matter what or to assume that any type of flexibility should be embedded in the system. Designers should keep in mind in their interventions that the purpose of flexibility is to improve expected future performance and value. Some strategies may be more valuable than others, or cost less, and should be prioritized. The framework and design procedures highlighted in this chapter are useful to rank order different design alternatives, in terms of benefits and costs, along economic and other metrics. Different methods in Phase 3 help generate a large number of possible flexible systems design concepts based on creativity techniques like brainstorming (Cardin et al. 2013), while others based on design structure matrix and change propagation may help narrow down the design space before going into computational analysis (Hu and Cardin 2015). The benefit of creativity-based techniques is that designers may come up with truly innovative solutions, but (too) many alternatives may need to be analysed computationally to identify the most valuable ones. In contrast, design structure matrix techniques go into more details early on, and may help reduce the realm of system design concepts generated and analysed, at the risk of ignoring easily accessible design opportunities that may be very valuable (i.e., losing the “forest” for the “trees”).

Future Directions

The field of flexibility in engineering systems design is highly multi-disciplinary. It is still relatively new (by academic standards!) and therefore still has much to offer in terms of future research directions and opportunities. An interesting aspect is that, given its nature, it often benefits from new research and developments in different disciplines. For instance, recent developments in artificial intelligence, machine learning, and data science are widely applicable in this field, with considerably untapped potential. The same goes for developments in digital twin modelling and 3D virtualization as more tools to support the design and decision-making process emerge. Although not exhaustive, this section provides an overview of potential future directions for research and applications.

Flexibility as Enabler of Sustainability and Resilience

With much uncertainty about the future, and ongoing threats from climate change, cyber and physical terrorism, and pandemics, engineering systems are exposed to massive risks in the coming decades. Such risks may disrupt global financial, urban, economic and political landscapes, as seen recently through the COVID crisis. To minimize risks and deliver a better future, engineers can play an important role by designing and deploying engineering systems that are more sustainable, with a view of making better use of limited resources, and resilient, to adapt and recover quickly from disruptions (Royal Academy of Engineering).

Research shows that flexibility can play a crucial role as a core, enabling paradigm to sustain and improve value in engineering systems design and make systems more resilient. Flexibility can help provide actionable strategies to mitigate risks and secure a better future. Flexibility enables sustainability – defined by the United Nations as "developments that meet the needs of the present without compromising the ability of future generations to meet their own needs" – by generating better value for systems that are already sustainable (e.g., renewable technologies), and by enabling system operators to deploy capacity and resources *if and when needed*. This reduces costs in present value terms, makes better use of limited financial and material resources by avoiding unnecessary capacity deployments (a valuable idea for future generations to satisfy their needs!), and thus adds value to society. Flexibility enables resilience, because it promotes "the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions" (United Nations). It provides important properties like adaptability and reconfigurability after an unexpected shock, so as to regain quickly pre-disruption performance.

An important future opportunity is to develop a systematic, agile design framework that helps address ostensible confusion and indecisiveness in design practice that may exist due to wide ranging and diverse views on sustainability and resilience. One benefit from flexibility is to provide a unifying framework to enable *both* concepts in engineering systems design, thereby enabling designers to be more focused in their efforts. Even though there are many facets to this important problem (Chester and Allenby 2019; Wied et al. 2020), flexibility is often discussed in both communities as an important enabling system property. This property can help further develop new design frameworks to help generations of future engineers better quantify the added value from sustainability and resilience, whether in terms of economic (e.g., profits, costs) or social (e.g., environmental, social, and governance or ESG) metrics (Schroders 2020).

Data-Driven Flexibility and Real Options

Up until recently, there has been very little work aiming at leveraging the power of data science and machine learning in the context of flexibility and real options analysis. For example, flexibility strategies still rely, by and large, on generic real option strategies (e.g., abandonment, capacity expansion, investment deferral) with exercise rules that are defined through human creativity (e.g., decision rules), and/or through Bellman's expected reward maximization principles (e.g., maximize expected discounted cash flow). Large datasets that are produced or used by engineering systems may provide new combinations or rules, timing, and strategies that may not be intuitive to human designers, but that could very well complement existing approaches, by providing unexplored value-enhancing solutions and reconfiguration policies. For example, one could specify the moves that are allowed for a system to adapt and reconfigure (e.g., deploy new phase, expand or contract capacity, abandon the project) based on a certain set of criteria (e.g., decision rules or policies, timings) and let the system combine these in different ways through a heuristic process to learn valuable strategies *from the data*. In this context, techniques such as deep reinforcement learning show great potential (see Caputo and Cardin 2022) and also generate other exciting new computational and mathematical problems (e.g., how to design optimal rules in a live, data-driven setting). The availability of large datasets also enables generation of better predictive models that can be used to improve scenario modelling in simulations. As a whole, there is a largely untapped potential for the development of a new data-driven formulation (or theory?) for flexibility and real options in engineering systems design.

Simulation Games and Empirical Studies

Another important direction for future research is to understand through empirical studies designers' and decision-makers' thinking and process during design activities and operations. Much research has been done where methods are demonstrated through applications in one or a few case studies. This may not be enough to fully validate a proposed new method.

Empirical studies enable collecting data on design and decision-making behaviour, describe, and make inference based on statistical analysis. For example, one may devise "treatments", i.e., different methods to train designers on how to make best use of a decision rules approach to flexibility analysis. The effect of the different treatments can be assessed as compared to a baseline, or control treatment, along different performance indicators, i.e., dependent variables, such as the number of times the decision rules are used, quantitative performance assessment, etc. While such studies are usually conducted in a controlled environment that may not exactly correspond to the real world, this approach is nonetheless complementary to case study research since it relies on statistical main and interaction effects, as opposed to case study evidence that takes longer to generate, and in smaller sample sets.

Combined with simulation games (or serious games, as used in Phase 5 of section "Design Frameworks"), empirical studies provide a valuable environment to test different design methods and procedures statistically. Inspired from military simulation games – *Kriegsspiel* being considered one of the oldest – they emulate an environment where behaviour and decision-making can be studied more thoroughly (Fig. 4). A few studies have taken an empirical approach to study flexibility in engineering systems (Cardin et al. 2013, 2015a; Jiang et al. 2018; Gil et al. 2015), but many more are needed to thoroughly validate new computational methods, algorithms, and digital processes emerging from research.

Decision Support Systems, Digital Twins, and 3D Virtualization

There is a need to develop and evaluate new computational aided engineering tools to support the design and decision-making process in industry. Many of the methods developed through research take the form of an algorithm or equations that are difficult to visualize for future users. There is a need to embed the research output into relevant software tools that can be used in a practical setting to support decision and policymaking.

This work is taking place at different scales. As mentioned before, recent developments in data science and machine learning provide wide ranging opportunities to make better use of increasingly accessible datasets on engineering systems. For example, at a national level, the UK's Data Analytics Facility for National Infrastructures provides datasets, models, and algorithms on infrastructures for research development (STFC et al. 2020). At a project and portfolio scale, work is ongoing to develop a control room for construction (Farghaly et al. 2021). Figure 5 shows another example through an integrated data-driven decision support system for designing large-scale engineering systems. The system integrates data visualization and analytics capability, optimization input and output visualization, as well as visualization of the optimization outputs in a 3D virtual environment. It overlays an optimization model developed for design and planning of waste-to-energy systems in Singapore (Kuznetsova et al. 2019). This kind of system provides designers and decision-makers with a tangible environment for training and decision-making, in an intuitive setting – as opposed to a set of complex equations.

The ideas above are in line with recent developments in digital twin modelling, where complex high-fidelity models are developed and improved over time from large datasets, and 3D augmented reality (AR) and/or virtual reality (VR) for digital project delivery (Nikoli et al. 2019; Whyte et al. 2019; Whyte and Nikolić 2018; Sacks et al. 2020). Such technologies are useful to support visualization, optimization, planning, and design decision-making under uncertainty in a highly immersive environment. They have been, however, largely unexplored in the context of flexibility in design. They have the potential to enhance significantly design activities, as well as training, and decision-making. By emulating closely a real-world environment and changing environmental and operational conditions, such system can be

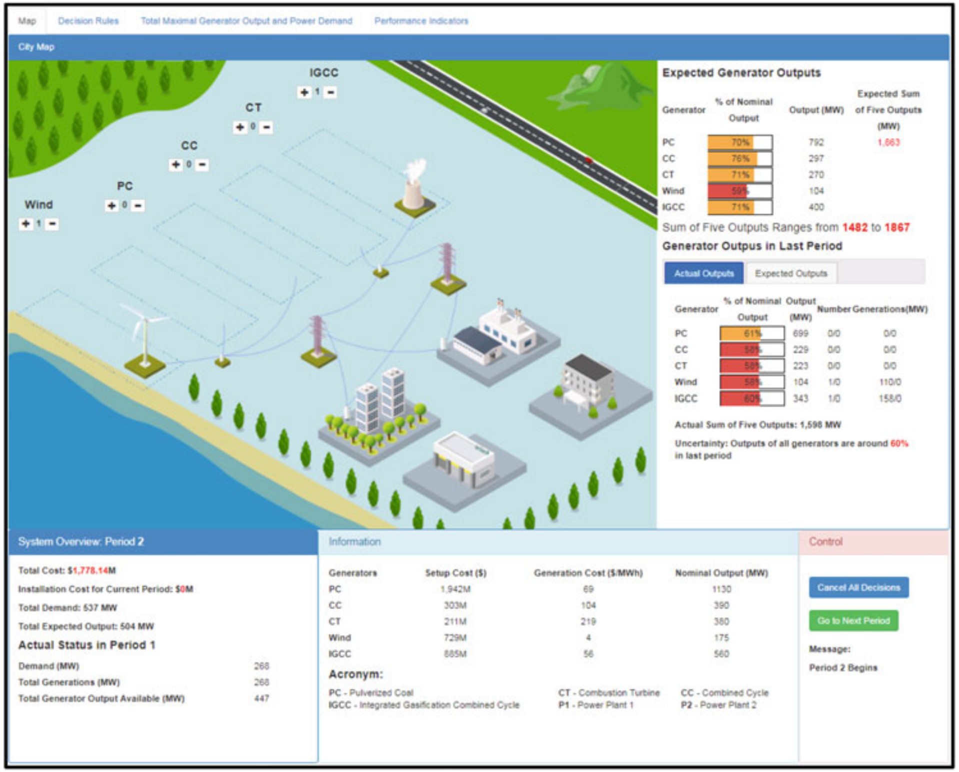

Fig. 4 Example of simulation game to study a decision rule formulation to real options analysis in design and operations of resilient and sustainable power systems. (Reproduced by permission for academic use only, "Development of a Simulation Game Platform for Flexible Generation Expansion Planning and Design of Power Grid Systems" in Proceedings of the 2018 Annual Conference, Institute of Industrial and Systems Engineers)

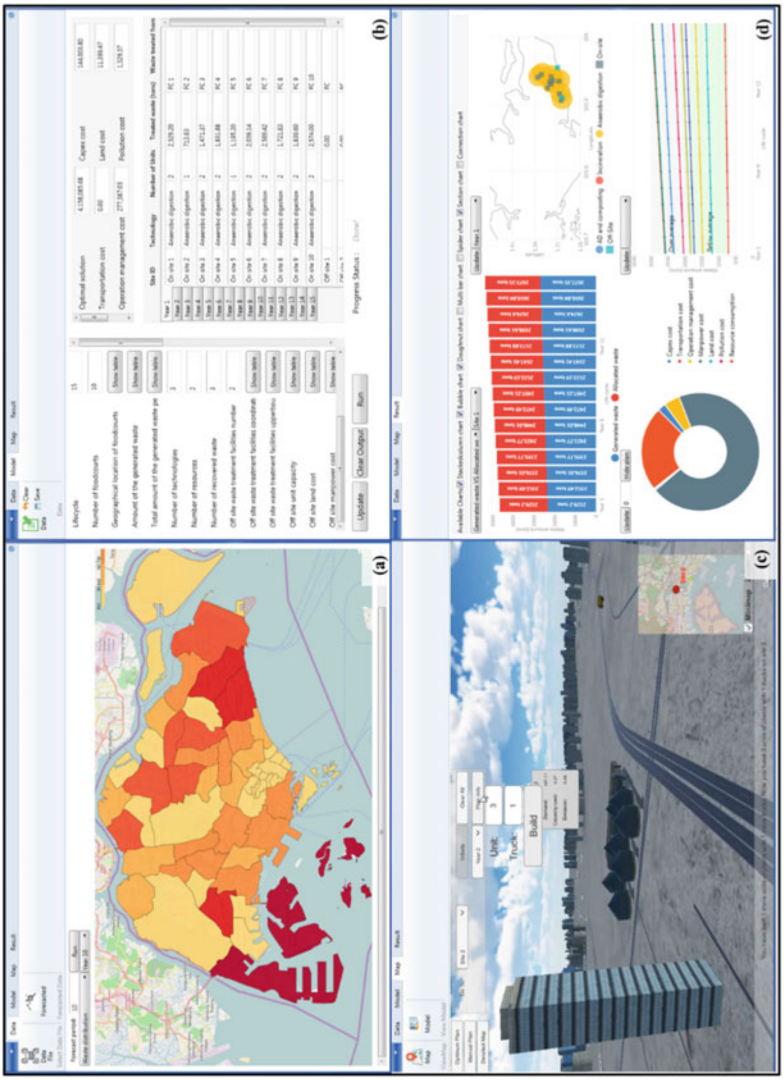

Fig. 5 Example of integrated data-driven decision support system for waste-to-energy systems. **(a)** Data analytics and visualization. **(b)** Optimization variable and parameter input definition. **(c)** 3D virtual environment. **(d)** Optimization output visualization

used to quickly prototype system design alternatives, test their performance in a simulated environment, and find optimal configurations. It can be used to train operators to operate the systems and determine when it is appropriate for the system to adapt, reconfigure, or evolve, which is especially useful for systems operating in a harsh environment, e.g., mining, drilling, and space. New knowledge on explainable AI (XAI) is particularly well suited to enhance the quality of design and operational decision-making. As a whole, digital twin modelling, complemented by AR/VR technology, XAI and decision-support systems yield very high potential for future research developments.

Conclusion

At a time where engineering systems face significant threats from climate change, pandemics, and terrorism, there is a need to change our approach to engineering systems design and management. There is a need to consider uncertainty explicitly early on in the design process, as a way to extract better value for society, through improved economic performance, sustainability, and resilience. Designing engineering systems for flexibility is of utmost importance for future generations of systems designers and operators, policymakers, and business leaders. It prepares systems for change, adaptation, reconfiguration, and evolution in ways that ensure not only better survivability, but also better value in the long term. While the field of flexibility in design emerged in part from real options analysis, it is now evolving on its own, and at a steady accelerating pace. Researchers continually develop and evaluate novel design methods and computational procedures to enable flexibility, as a systematic value enhancement mechanism. The community is growing, as seen by the expanding volume of literature on the topic. This chapter provides an overview of such evolution over recent decades, motivated by an important need in industry and policymaking. It gives an overview of existing design frameworks, methods, and procedures to support design activities in practice and highlights important challenges and limitations. The overview exposes the multi-disciplinarity of the field, which involves finance, engineering design, optimization, statistics, and uncertainty modeling, with applications in many relevant sectors such as aerospace, automotive, energy, real estate, transportation, and water systems. The overview paves the way to exciting and applied research opportunities, much needed in industry and academia, involving sustainability and resilience, data-driven real options, empirical studies and simulation games, as well as AI and machine learning for design decision support, digital twin modelling, and 3D virtualization.

Cross-References

► Architecting Engineering Systems: Designing Critical Interfaces
► Designing for Emergent Safety in Engineering Systems
► Designing for Technical Behaviour

► Engineering Systems in Flux: Designing and Evaluating Interventions in Dynamic Systems
► Properties of Engineering Systems
► Risk, Uncertainty, and Ignorance in Engineering Systems Design
► Systems Thinking: Practical Insights on Systems-Led Design in Socio-Technical Engineering Systems
► Technical and Social Complexity
► Transforming Engineering Systems: Learnings from Organising Megaprojects

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Engineering Systems in Flux: Designing and Evaluating Interventions in Dynamic Systems

21

Pieter W. G. Bots

Contents

Abstract

This chapter discusses the threefold challenge of designing effective interventions in engineering systems that are constantly changing: (1) a designed socio-technical artefact should improve system performance not only under present conditions, but it must also be functional when conditions change, be it autonomously or due to interventions performed by others, and (2) the actual intervention of implementing the artefact should be planned such that it does not disrupt functional processes elsewhere, while (3) the implementation process should be impervious to such *contingent processes*. To meet this challenge, engineers can deploy different strategies: design strategies that will enhance the robustness of an

P. W. G. Bots (✉)
Faculty of Technology, Policy and Management, Delft University of Technology, Delft, The Netherlands
e-mail: p.w.g.bots@tudelft.nl

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artefact, its flexibility, or its capacity for (planned) evolution; strategies that will stabilise the context of the artefact; and implementation strategies that will contain and shield the intervention. This chapter reviews these strategies, discusses how they relate to systems engineering methodologies, and then highlights exploratory modeling and participatory modeling as methods for ex ante evaluation of interventions in dynamic engineering systems.

Keywords

Adaptive design · Engineering systems · Flexible design · Implementation plan · Institutions · Planned intervention · Robust design

Introduction

To intuitively grasp the concept of engineering systems in flux, consider the following joke:

> A cardiologist's car breaks down and she goes to a mechanic to get it fixed. After everything is done, the mechanic asks the cardiologist, "Here's what I don't understand. I fix engines, and so do you, albeit human ones, so why do you get paid ten times more than I do?" The cardiologist then turns the ignition on and says, "Try it with the engine running." (Anonymous 2019)

The mechanic points out the similarity of their profession: they are both engineers. Indeed, a cardiologist (or more precisely a cardiac surgeon) and a mechanic both perform a planned intervention that typically involves placing an *artefact* (e.g., a valve) in some *target system* (a heart; an engine) such that it affects a target process (pumping; a four-stroke cycle) such that it improves certain *measures of performance* of the target system (ejection fraction and valve gradient of the heart; horsepower and emissions of the engine) typically to enhance the performance of an encompassing *system of interest* (a human body; a vehicle) to serve the needs of some *client* (a patient; a driver).

The cardiac surgeon then pulls a bluff: she suggests that the target system she intervenes in is running during this intervention, whereas in practice she replaces a cardiac valve in the arrested heart while a heart-lung machine is keeping up the entire circulatory system. The actual difference between their engineering jobs lies in the properties of the *system of interest*: the organs of a living body degrade rapidly when its blood circulation is stopped, and the patient will die, whereas a car will function as new even when restarted after an engine overhaul that took weeks to complete.

The main takeaway of this metaphor is that to understand what it means to design in the context of engineering systems *in flux*, and appreciate the various design strategies and methods, key concepts like system, flux, and intervention must be clarified. Section "Engineering Systems in Flux: Some Terminology" therefore provides a basic terminology for this chapter. In the subsequent sections, different aspects of "engineering in flux" are elaborated in more depth and linked to related bodies of academic thought. Section "Strategies for Designing Artefacts in Systems that Are in Flux" reviews generic strategies for designing artefacts that can cope with flux. Section "Systems Engineering Methodologies: Strategies for Managing Flux" discusses how engineering methodologies relate to flux by considering the complex internal dynamics of systems engineering projects and the structures and strategies for managing them. This highlights the pivotal role of institutional design and how this sets limits to interventions in engineering systems in flux. Section "Modeling for Design and Evaluation of Interventions in Dynamic Systems" then addresses the question how models can support the design and evaluation of engineering interventions despite the uncertainties inherent to flux. Section "Conclusion" concludes this chapter with a summary of the main ideas.

Engineering Systems in Flux: Some Terminology

Being the subject of this entire handbook, the concept of *engineering system* needs no introduction. Typical for engineering systems is that they are human-designed, dynamic systems that have significant human complexity as well as significant technical complexity (De Weck et al. 2011). Dynamics and complexity entail nested structures and processes, both physical and social, that relate and interact in many ways. Being human-designed entails that some subset of these structures is artificial (Simon 1981), i.e., have been intentionally created by humans. Systems engineering, then, is an intentional process of devising and implementing such artificial structures. This implementation process constitutes a planned intervention in the engineering system.

Engineers typically plan and then perform interventions to improve system performance on behalf of some client. What is seen as "measures of performance" and "significant improvement" is defined by the client and will be situated (i.e., relate to a particular subsystem) and subjective (i.e., depend on the client's perceptions and preferences). Given that humans will always seek opportunities for what they see as performance improvement, large-scale engineering systems are in perpetual flux simply because numerous interventions take place concurrently, targeting a variety of subsystems on behalf of a variety of clients. Being interrelated, processes in one subsystem will affect processes in other subsystems, these changes will prompt for new interventions, and so on.

Most artefacts are themselves nested structures, and interventions likewise are nested processes. For the sake of conceptual clarity, a single intervention is assumed to be aimed at improving the measure of performance of one particular process (the *target process*) within some subsystem (the *target system*) and to consist of implementing one particular artificial structure (the *artefact*) by placing it within the target system. This may involve connecting it to the structures – natural or arteficial – that were already in place prior to the intervention, shaping the target process as it was, and in this way co-determining its original performance. With the artefact in place, the target process will be shaped differently and perform better.

The relation between artefact and target process is called the *function* of the artefact. A *functional artefact*, then, is an artificial structure that is shaping the target process as intended by the engineer. In the same vein, a *process* is considered as functional when it enhances the measure of performance of the client's *system of interest*. Conversely, processes (and the structures shaping them) are considered dysfunctional when they lower system performance, and non-functional when they do not affect the client's interest.

The *target* system need not be chosen by the client. More likely, the client seeks to improve the performance of a larger system: the *system of interest*. The engineer will analyse this system, diagnose which subsystems constrain performance most, and then propose interventions that will improve the performance of these specific subsystems. Based on the engineer's findings, the client typically chooses or prioritises the proposed interventions for these target systems. This may involve trade-offs for the client, as interventions may also affect the performance of processes outside their target system. Such *contingent processes* may also be of interest to the client: directly because they are functional processes as well or indirectly because, although external to the client's *system of interest*, they constitute functional processes for third parties. The impacts – positive or negative – of interventions on processes outside the scope of the client's *system of interest* are called *externalities*. Even when the client is indifferent to the affected parties, systems engineering ethics dictate that engineers should identify and factor in such *externalities* as well.

The humour of the joke of the cardiologist and the mechanic lies in its suggestion of the painful image of a mechanic foolishly inserting his hand into a spinning jumble of interlocking steel parts. For the mechanic, evidently, the target process itself (the engine running) physically prohibits performing the intervention. For the cardiac surgeon, this need not apply. To place an aortic valve, she can even opt for an intervention "with the engine running", as for a minimally invasive transcatheter procedure, the heart need not be arrested. But for an open-heart procedure, she needs to solve the problem of creating suitable conditions for implementing the artefact (anesthetised patient, open chest, arrested heart) while also maintaining adequate performance of *contingent processes* (blood oxygenation and circulation) during the intervention.

Interventions will be more challenging to the extent that they affect or are affected by processes in the target system or elsewhere in the *system of interest*. When the road surface of a motorway in a busy metropolitan area has to be renovated, or a dam is to be constructed in a river, such interventions aimed at furthering the interest of the client (people needing transport, flood protection, irrigation, and hydropower) need to be planned and performed as meticulously as open-heart surgery, or they may actually harm these interests. In both examples, the target process (flowing traffic or water) impedes the intervention, but cannot be stopped (unlike the running car engine). To perform the intervention, the flow must be diverted for some time (similar to the patient's blood circulation). This diversion typically requires additional artefacts, notably temporary structures that deviate the flow from the working area and can be moved over time as the implementation process proceeds step by step.

This highlights that an intervention is itself a process, typically comprising a set of smaller interventions. In addition to placing new layers of tarmac or concrete, renovating an intersection will, for example, also comprise placing barriers and road signs to deviate the traffic flow, making formwork for the concrete, and making schedules for workers. Barriers and formwork (physical structures), work schedules (institutional structures), and road signs (both physical and institutional) are again artefacts. In this case, barriers and road signs are *transient* artificial structures that are placed within the target system (the intersection) to reshape the target process for a period of time so that it permits performing the intervention. This type of transient artefact, designed to enable the intervention while preserving adequate performance of *contingent processes*, may temporarily lower the measure of performance of the target process (slower traffic flow). The formwork and work schedules are also transient artefacts, but these are designed to enhance the performance of processes that actually implement the new road surface (the *primary* artefact).

The idea of *planned* intervention entails that in addition to the artefact that will enhance the target process, the engineer also designs another artificial structure: the implementation plan. This plan should shape the process of implementing the primary artefact (step by step) according to its design, such that the contingencies and *externalities* of this intervention are minimal (or at least acceptable).

Being a structure designed to shape a process to improve its measure of performance (implementation efficiency), an implementation plan is itself an artefact. Being a prescriptive procedure for human action, an implementation plan is an *institutional* artefact. This highlights that planned intervention takes place within a context of social norms and formal rules (Ostrom 2005). These institutional structures are an intrinsic part of engineering systems.

To become functional, a primary artefact and its implementation plan must *both* be designed in conformance with their "contextual" institutional artefacts. For open-heart surgery, these would include, for example, the ISO 5840 standard for cardiovascular implants and the professional standards and guidelines that shape the cardiac surgeon's clinical practice.

Likewise, a primary artefact and its implementation plan are *both* susceptible to flux, albeit on a difference timescale. Both artefacts should remain functional during their "lifetime", but the "lifetime" for an implementation plan (the time required for surgery and recovery) is typically much shorter than for the primary artefact (5–10 years for tissue valves, much longer for mechanical valves). Also, different types of flux will affect the performance of the two artefacts differently (the implementation process would be greatly disturbed if the patient wakes up and starts moving, whereas after recovery the valve will be insensitive to such movement).

Although interventions constitute a major source of flux in engineering systems, flux evidently also results from a wide variety of natural processes: corrosion, infection, insolation, precipitation, sedimentation, sea-level rise, and demographic developments are but a few examples. All these processes may cause artefacts to become non-functional or even dysfunctional. Designing in engineering systems in flux therefore entails (1) devising a primary artefact that, once implemented, will improve a particular measure of performance of the *system of interest* even when conditions change and (2) devising an implementation plan (plus the transient artefacts it requires, plus – recursively – their implementation plans) that will ensure adequate performance of the implementation process and *contingent processes*.

The next section reviews five categories of strategies that engineers may adopt to achieve this. These categories are not mutually exclusive. Strategies for designing the primary artefact such that it will function even when conditions change (design for robustness, flexibility, and/or evolution) may be combined with strategies for keeping conditions stable (mitigate flux). Moreover, since implementation plans can be seen as institutional artefacts, the strategies for implementation planning typically reflect strategies from the other four categories. Their recursive application is pervasive and entrenched in systems engineering thinking and practice. The systems engineering methodologies reviewed in Section "Systems Engineering Methodologies: Strategies for Managing Flux" are keen examples of institutional artefacts designed to enhance the performance of intricately nested processes of design and implementation of likewise complex primary artefacts.

Strategies for Designing Artefacts in Systems That Are in Flux

Although the specific measures of performance will vary widely, depending on target system and client, some characteristics of artefacts, such as quality, safety, usability, operability, reliability, and maintainability, are considered to be generally desirable. Some of these "ilities" as De Weck (2011) calls them relate specifically to flux: *robustness* and *flexibility*.

Robustness is the ability of an artefact to function as intended in a wide range of conditions. In other words, a robust artefact is insensitive even to significant changes in its context (e.g., earthquake-resistant buildings) or in the target process it shapes (e.g., power cables that can withstand loads up to several times their nominal capacity). Robustness differs from resilience in that a robust artefact will continue to function even under extreme conditions, whereas a resilient artefact may fail to function but still retain the ability to quickly resume its functioning once conditions have normalised again (e.g., an installation that automatically reboots after a power failure).

Flexibility is the ability of an artefact to respond to a need for different functions. What this entails depends on the phase in the artefact's lifecycle. For the design phase, i.e., when the artefact exists only on the drawing board, flexibility refers to the relative ease with which the conceived artefact can be changed to (also) perform a new function or be connected with other artefacts. A flexible design affords a wider range of interventions. This type of flexibility is called adaptability when it is easy to change the design so that the artefact will perform its original function in a context that sets very different conditions, extensibility when it is easy to change the design such that the artefact can perform new functions in addition to its original function, and evolvability when the design has such generic properties that, over a longer time, it affords successive changes such that new "generations" of artefacts can perform radically different functions. The term agility applies when a design can be adapted or extended in a very short time.

For the operation phase, i.e., when the artefact has been realised and implemented within its target system, flexibility is the ability of the artefact to perform multiple functions, i.e., shape *other* target processes in ways that *also* enhance the performance of the *system of interest*. A smartphone is in this sense very flexible since it affords talking to someone while simultaneously taking a picture and checking one's e-mail or calendar or playing a game. Artefacts that can only perform one function at a time can still be flexible in that their design affords that their structure is changed into different configurations such that it can perform different functions. The Swiss army knife is the iconic example of this type of flexibility, which De Weck (2011) calls reconfigurability. The ability of artefacts to easily adjust to the need to expand its capacity for performing its function is called *scalability*.

De Weck's thorough semantic analysis of the "ilities" of designs and artefacts affords a categorisation of intervention strategies that system engineers may adopt to cope with flux.

Design for Robustness

This category comprises design strategies that anticipate on exogenous change in conditions while assuming that the functions and the client needs they stem from are stable. Although the literature on methodologies for robust design pertains mainly to industrial products (Arvidsson and Gremyr 2008; Christensen et al. 2012), their basic principles – awareness of variation and insensitivity to "noise" throughout all "lifecycle phases" of the artefact – are generic. This applies even more to the design principles that Knoll and Vogel (2009) propose for civil engineering artefacts:

- Focus on loads. Structures must be strong enough to withstand high loads. Identify all functional processes as well as non-functional processes that put strain on structures. Establish the error of estimate for the magnitude of loads.
- Foresee and prevent interior flaws. Identify structural properties that are critical. Challenge why the design makes them strong enough. Make failure/breakdown mechanisms explicit. Pay special attention to structures that are sensitive to error during implementation.
- *Consider* structural hierarchy. Focus on primary structures, i.e., those bearing the main load of the processes they shape. Identify cascading failure mechanisms, i.e., how failure of substructures may cause adjacent structures to fail ("domino effect") and/or cause high loads on structures higher in the hierarchy (escalation).
- Foresee external causes. Identify processes and events that may cause exceptional loads on structures. Gauge the extent of such loads and formulate "maximum credible events". Consider the effects of such events when they occur simultaneously ("worst case" scenarios).

Practicing these principles will reveal which system components are critical, and this will prompt designers to consider alternative strategies for making these components less prone to failure. Two common strategies for achieving this are over-dimensioning (designing structures to withstand loads well beyond their original specifications, possibly even beyond those foreseen in the “worst case” scenario) and *redundancy* (duplicating system components such that their function remains fulfilled in case a component fails). Design strategies to prevent, or at least contain, cascades of failing structures include periodically adding strong elements (“zipper stoppers”) among clusters of brittle elements to stop the progression of the failure, and placing structures designed to fail (“sacrificial structures”) in order to protect the rest of the structural system from excessive loads (e.g., fuses, circuit breakers, pressure valves). Still, artefacts that have been designed for robustness may become brittle over time, not only because loads grow to exceed their planned capacity but also as its structures are altered such that the assumptions that were true at design time no longer hold.

Design for Flexibility

This category comprises design strategies that anticipate change in the functions and/or capacity of the artefact in response to changing client needs. Cardin (2014) has synthesised a wide range of such strategies (design methods, procedures) in an action-oriented framework that distinguishes five design activities that aim specifically at identifying and utilising opportunities for making a design more flexible:

1. *Create a baseline design.* This design should still be conceptual, so focus on design concepts that address high-level functional requirements. Consider existing designs, but ignore their detailed functional specifications, load estimates, and constraints that may have been provided by the client. The set of design concepts (“design architecture”) must be specific enough (e.g., a detailed sketch or physical prototype) to allow consideration of uncertainty and flexibility in activities 2 and 3.
2. *Recognise uncertainties.* Identify uncertain factors that will affect the performance of the artefact in any phase of its lifecycle. Consider endogenous factors (related directly to the artefact, and the organisations involved in its design and construction) as well as exogenous factors (related to users, markets, politics and culture). Model the identified uncertainties such that their consequences can be assessed in activity 4.
3. *Generate flexibility concepts.* Distinguish between flexibility of the design and flexibility of the artefact. Develop design concepts as combinations of a *strategy*, i.e., the process by which the artefact will adapt in response to future events uncertainty, and an *enabler*, i.e., the structural elements in the design that afford this adaptation and how it is managed.
4. *Explore the design space.* Develop quantitative procedures to evaluate the lifecycle performance of a design. Assess which flexibility concepts provide better lifecycle performance relative to the baseline design. Use this assessment to select high-potential enablers, and formulate decision rules for when to apply the associated strategy.

5. *Manage the process.* This applies to activities 1 through 4 in the design process but also to processes of implementation, operation and decommissioning of the artefact. For the design process, process management entails motivating stakeholders (client, corporate management, designers, market analysts) to think in terms of "flux and flex", stimulating creativity as well as rigorous methods for evaluation under uncertainty. For the operation and decommissioning, it entails knowing the designed-in flexibilities and monitoring triggering conditions for exercising them.

Flexibility enablers can be found by analysing the baseline design to identify design variables that are most sensitive to changes in client needs or that when changed will cause need for more changes. Reconsidering the structural hierarchy of the baseline design and the interfaces between subsystems in the baseline design is also a good heuristic for localising flexibility enablers.

Adaptability may be increased by adding "real options" (De Neufville et al. 2006), i.e., investments that are not of immediate value but will permit (or greatly reduce the cost of) modification or expansion sometime in the future. The enabler for such options can be (a combination of) over-dimensioned structures (e.g., the main arteries in a network, or the foundation of a building) that permit upscaling or extension, reconfigurable structures that permit adaptation to different market demands (e.g., office buildings that can be converted into apartment buildings), and modular structures that permit efficient decommissioning and reuse of components (e.g., vehicles designed for disassembly).

Design for Evolution

Where design for robustness and design for flexibility can be seen as *hedging* strategies that aim to mitigate the consequences of flux for planned intervention, design for evolution can be considered as a *shaping* strategy (Dewar 2002) as it aims to harness contextual processes of change as part of the intervention. Such strategies can be particularly effective when the contextual dynamics are well understood, affording adequate prediction of the evolution of a functional artefact. A small-scale example of this design strategy is "tissue engineering", where a degradable scaffolding structure is placed in a human body to shape cell growth processes to form new bone, skin, or heart valves (Neuenschwander and Hoerstrup 2004). On a much larger scale, "Building with Nature" projects (Van Slobbe et al. 2013; De Vriend et al. 2015) harness slow natural hydro-morphological processes to form structures that mitigate erosion and flood risk.

For large-scale engineering interventions such as infrastructure development and city planning, evolution of the artefact mainly depends on social processes. Human agency makes the circular causation in the development of urban areas and infrastructures even more complex (and hence less predictable) than the feedback mechanisms in natural processes (Gifford 1995). The interactions between actors (planners, designers, contractors, operators, users) cause emergence of patterns perceived by these same actors, and this (re-)interpretation of the system causes them to alter their interactions, giving rise to new patterns, and so on (Holtz et al. 2015; Portugali 2000, 2008). When designing for evolution, city planners and infrastructure engineers may seek to enhance their capacity for prediction through modeling (cf. section "Modeling for Design and Evaluation of Interventions in Dynamic Systems") but more often will rely on design for flexibility approaches or on incremental approaches based on pilot projects (Vreugdenhil et al. 2010).

In projects embedded in "open source" product development communities (Bonvoisin et al. 2017; Scacchi et al. 2006), the design process itself is evolutionary because it implements the Darwinist principle of evolution through mechanisms of variety and selection. When new requirements emerge, these are broken down into modular tasks and communicated to let community members decide what to work on. Bottom-up integration may rely on a core team of senior community members who, being most knowledgeable and skilled, assess the quality of a contribution before its integration. Alternatively, the integration strategy may also be to permit contributors to integrate their work as they see fit and rely on other members to improve it or replace it by a better contribution. Both strategies reflect that evolutionary design approaches balance capacity for centrally planned and coordinated change (to accommodate the complexity of the task) with the capacity for decentral and incremental change (to accommodate changing client needs).

Mitigate Flux

This category of strategies for dealing with flux fundamentally differs from the previous three in that the strategies aim at reducing or containing the variability in the context of the intervention, rather than at making the artefact insensitive or adaptive to contextual change. Mitigating flux can also be seen as a *shaping* strategy (Dewar 2002) but – quite unlike design for evolution – one that aims to maintain the status quo. Groynes and breakwaters are examples of physical structures designed specifically to protect coasts and riverbanks by mitigating water flows that would otherwise cause erosion. Likewise, shock absorbers can be used to protect more sensitive substructures against abrupt movements.

On a project level, flux mitigation strategies may, for example, seek to limit "scope creep" due to changing client preferences by anchoring specifications and procedures for scope control in contracts (Collyer and Warren 2009). To stabilise the industry sector they are part of, corporate actors use institutional artefacts such as patents, licensing contracts, and standards. Holgersson et al. (2018) demonstrate how (coalitions of) corporate firms in the mobile telecommunications sector used these intellectual property strategies to preserve their dominant position, and how interventions of this type by newcomers can first disrupt and then reform. An apparently paradoxical finding is that when disruption leads to a shift from soft institutions (implicit contracting and gentlemen's agreements that rely on social norms) to hard institutions (formal rules embedded in patents and licensing contracts and enforced through litigation), dynamics increase and stability decreases. When "patent wars" increase the transaction costs (North 1990; Williamson 2000) in an industry sector to the level where they impair new product development, the sector will design formal institutions that increase stability, such as technological standards coupled with the obligation for all firms to license standard-essential patents at fair, reasonable, and non-discriminatory terms.

The study by Holgersson et al. (2018) shows that coalitions of firms can use institutions both to mitigate flux and to stimulate flux. When striving to maintain a monopolistic position, they will design propriety standards and develop restrictive patent licensing strategies; when aiming to stimulate other firms to adopt and extend their technologies, they will use liberal licensing strategies and promote open standards. This reflects that institutional design (Alexander 2005; Koppenjan and Groenewegen 2005) within engineering systems may focus on institutional structures that provide a relatively stable context for processes of systems engineering but also on strategies that stimulate technological innovation. Systems engineering methods as strategies for managing flux will be reviewed in the next section. Strategies for inducing flux, for example, to stimulate innovation, are beyond the scope of this chapter.

Design of Implementation Plans

An implementation plan should shape the process of performing a planned intervention in an engineering system in flux such that (1) it is effective, i.e., implements a functioning artefact; (2) it has limited negative impact on the performance of the target process and *contingent processes*; and (3) it delivers on time and within budget.

The first two requirements relate to flux in the sense of intervening "with the engine running". When these requirements are not critical, engineers are likely to take the approach of the mechanic repairing an engine because this is more efficient. This interruption strategy means halt the target process, typically using transient structures to isolate the target system from the larger *system of interest*; then implement the artefact; then reconnect the target system; and finally, restart the target process. But when the intervention must be performed without interrupting the target process, this typically requires some form of redundancy. Depending on the target system situation, one of the following strategies can be adopted:

- Augmentation strategy. Create in situ the additional structures that will enhance performance of the target process. Test, and then deploy these new structures by connecting them with the larger *system of interest*. This strategy is feasible when the target system is sparse in the sense that it provides ample space for implementing additional structures while keeping the current structures intact and functioning. Typical examples are adding new servers to a data centre or expansion of networked infrastructures (rail, road, cables, pipelines) when additional lines can be built along new trajectories or in parallel to existing ones, and

their connection to nodes on either end can be a controlled and virtually instantaneous operation.
- Substitution strategy. Use redundant capacity of existing structures in the *system of interest* to keep up the performance of the target process, or implement new transient structures that can achieve this for the duration of the intervention. Then perform the planned intervention in the target system using an interruption strategy. Then when the (now enhanced) target process has been resumed, remove the transient structures. This strategy is feasible if the *system of interest* can temporarily provide the required additional capacity or space. In a meshed transport network, traffic can be rerouted. The hard shoulder of a motorway can be used to compensate for the traffic capacity that is lost while reconstructing the pavement of a lane. A heart-lung machine affords open-heart surgery because it can substitute the circulation and blood oxygenation functions of these organs. Reservoir engineers will use redundant capacity when geological conditions allow diverting a river away from the build site via an adjacent valley or create such capacity by digging tunnels.
- Piecemeal strategy. Reduce the impact of the intervention on performance by splitting the intervention into a series of smaller ones that, because of their limited scope in time and space, are easier to perform with a substitution strategy or have less impact on system performance when performed with an interruption strategy. Piecemeal strategies evidently work well for implementing modular artefacts such as NASA's International Space Station that have been designed such that implemented component modules can function independently from the modules still awaiting their implementation. Another example is the timed implementation of software updates for operating systems of smartphones: rolling out an update in phases, each phase targeting a specific user group controls not only the load on the software servers but also the disruption of the target system.
- Control/mitigation strategy. Condition processes in the context of the target system such that they interfere less with the implementation process and/or are less sensitive to interruption of the target process. Heart surgeons administer medication that will slow down the patient's heart rate to facilitate a minimally invasive procedure. System operators and service providers typically schedule and announce maintenance windows so that users can anticipate and shift critical processes to other moments. System engineers smoothen transitions to new technologies by announcing deprecation of standards well in advance but also design artefacts with "forward compatibility" to prolong their operational lifetime.

The part of the implementation plan that structures the "core" intervention – implementing the artefact within the target system – generally reflects the structural hierarchy of the primary artefact, simply because realisation of an artefact entails realisation of its parts. Hence subsystems imply implementation sub-processes. But the implementation planning strategies show that implementation entails additional processes. Some structures in the target system may need to be modified to redirect the target process or to achieve that the primary artefact can be connected to them. In addition, the transient structures needed to implement the primary artefact, or to mitigate interference with *contingent processes*, must also be implemented (and eventually removed). Designing these additional processes – recursively – as planned interventions (which implies also considering and resolving their impact on *contingent processes*) will eventually produce a complete set of implementation processes.

Given this set, project planning methods like PERT/CPM (Moder et al. 1983) are useful to improve implementation performance in terms of time and budget. The project planning term for the decomposition of a process into sub-processes is activity breakdown structure. The bottom layer of this breakdown defines the "atomic" sub-processes (*activities*). Planning adds the fourth dimension: time. The hierarchical relation of an activity breakdown structure does not determine the precedence relation between the activities; it merely defines them as "pieces of the puzzle". Planners establish the precedence relation by checking for each activity X which other activities *must* have been completed before X can be performed. Larger substructures must typically be implemented before their smaller substructures can be connected to them. The resulting precedence graph allows planners to plan activities in parallel and apply the critical path method (CPM) to minimise overall project time.

Implementation plans are institutional artefacts and hence must themselves be "implemented" within existing institutions, both formal (contracts, permits, labour laws, safety regulations) and informal (common social routines and professional practices). Ideally, they should be compatible with the plans for other interventions, but the image of workers breaking up a newly paved street for lack of coordination between the roads department and the water and sewer department is – alas! – all too familiar. A rigorous project plan with an elaborate activity breakdown structure optimised for efficiency may lack resilience. Just like physical artefacts, an implementation plan should preferably be robust and flexible. In fact, each of the four categories of design strategies reviewed earlier in this section will help design implementation plans that can cope with flux. Pilot projects serve as "sacrificial structures". Forward compatibility can be seen as a "real option". Adding slack resources to critical steps in an implementation plan is a form of "institutional overdimensioning" to prevent "cascading failure" of the entire plan.

Systems Engineering Methodologies: Strategies for Managing Flux

Systems engineering methodologies (e.g., Sage and Rouse 2009; Walden et al. 2015) can be seen as institutional structures that have been designed by engineers to shape the processes of designing and performing interventions in engineering systems to enhance their efficiency, i.e., the ratio of the functionality of the artefact over the resources used (time and budget). These methodologies reflect the recursive application of "design thinking" not only to a primary artefact and the artefacts that shape its implementation process (the implementation plan and transient artefacts) but also to a third category of artefacts: those that shape the processes of designing the primary artefact and all other artefacts needed for its effective implementation, operation, and eventual decommissioning. Such "methodological" artefacts typically "codify" best practices as formal procedures and standards that, when enforced, shape the decision processes of engineers as they diagnose and decompose the *system of interest* and conceive, test, and evaluate interventions in identified target systems.

Interventions hinge on changing structures by (re)placing artefacts in selected target systems within the *system of interest* so that the overall performance of the *system of interest* improves. Systems engineering methodologies therefore focus on the primary artefact. They commonly structure the systems engineering process in phases that follow the "lifecycle" of this artefact. Although the number and names of phases vary per publication, they typically follow this pattern:

1. *Inception:* a process of growing awareness of needs that the *system of interest* does not fulfil (unsatisfactory system performance).
2. *Design:* a process of identifying the target system within the *system of interest*, specifying its functions and requirements by operationalising their measures of performance, conceiving and assessing alternative options for improving performance (global design of artefact), and detailing the preferred option (detailed design of artefact and its implementation plan).
3. *Implementation:* a process of realising (in the literal sense of "making real") the design produced in the previous phase, i.e., constructing and deploying the artefact within the *system of interest* as planned.
4. *Operation and maintenance:* a process of keeping the artefact functional so that it shapes processes within the *system of interest* as intended and intact so that it continues to do so.
5. *Decommissioning:* a process of dismantling and/or removing the artefact from the *system of interest* so that it no longer shapes processes within this system.

Systems engineering methodologies focus most strongly on the design phase, as in this phase the processes in the subsequent phases should be anticipated and structured by the design. Although authors emphasise the iterative nature of the design phase, the methodologies aim for closure. They prescribe structures for decision-making processes (Parnell et al. 2011) that generally follow the (bounded) rational *intelligence-design-choice* pattern (Simon 1981) that involves divergence and convergence, but the end product is a design that consolidates the many choices made during the decision process in a design that specifies the artefact in such detail that it can be realised and implemented.

The graphical representation of the V-model of systems engineering (Forsberg and Mooz 1991) in Fig. 1 highlights this decision focus by emphasising the stage gate decision points. Using the terminology of sections "Engineering Systems in Flux: Some Terminology" and "Strategies for Designing Artefacts in Systems that Are in Flux", the first point, at the end of the *Needs Assessment* and *Concept Selection* processes (Phase 1), corresponds to the selection – after analysis and diagnosis of the *system of interest* – of the target process and the "baseline design"

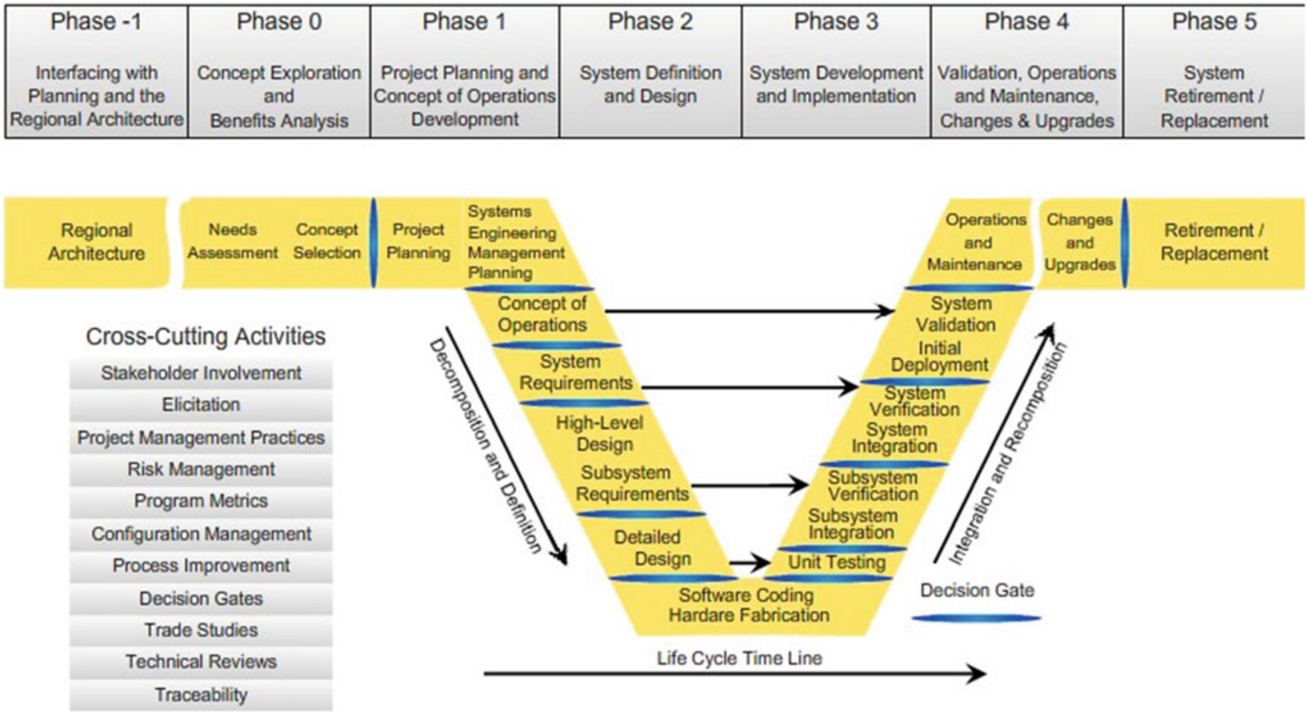

Fig. 1 V-model of the systems engineering process (FHA 2009)

of the artefact. The stage gate decision points at the end of each sub-process in Phase 2 concern the breakdown of the overall intervention into smaller ones, each targeting specific sub-processes with specific substructures that can be designed more or less independently. Likewise, those in Phase 3 mark the closure of steps in the implementation plan. The idea of such stage gate decisions is that at those points in time specific design and implementation choices are "frozen" to provide a stable structure for subsequent decision processes.

The decomposition of the design task typically follows the structural hierarchy of the artefact. Moving along the downslope of the V, the client needs are translated to main functions and requirements, which prompt decomposition into subsystems. Detailing the functions and requirements for these subsystems prompts further decomposition down to the elementary level (bottom of the V), where a system element is an artefact that can be bought "off the shelf" or can be fabricated to specifications. Moving along the upslope of the V, elements are assembled first into units, which are assembled into components, which are integrated further into subsystems until the completed artefact is ready to be deployed.

The diagram in Fig. 1 is limited in that it simplifies the crucial mechanisms of decomposition and integration as two arrows, whereas these mechanisms mean that each "box" in the V comprises a multitude of concurrent design processes and implementation processes, each dealing with one particular subsystem, component, unit, or element of the complex artefact that is being designed and implemented within the target system. Likewise, the horizontal arrows represent a multitude of concurrent processes of validation and testing.

These testing and validation processes at all levels (the horizontal arrows) may reveal unsatisfactory performance (possibly due to evolving needs). This then may call for changes in the design that challenge earlier made choices, not only regarding the tested element, unit, component, or subsystem but possibly also regarding their connected parts.

That changes to the design of one part can call for redesign of other parts highlights that the decision processes of concurrently designing engineers are contingent to the extent that the target processes of the artefacts they are designing are contingent. When such contingencies exist, engineers must coordinate their decision processes so as to ensure that in structural and functional properties, one artefact will not impair those of other artefacts and likewise that their implementation plans do not interfere. Or phrased positively, engineers must coordinate to achieve synergy.

The complexity of a systems engineering project thus has two related dimensions: (1) the multiplicity of structural connections between parts and (2) the dynamic interaction between concurrent design and implementation processes as they progress (Whitty and Maylor 2009). Hence, a strategy common to most systems engineering methodologies is to decompose the artefact so that the resulting hierarchy of substructures minimises the number of their connections and interactions. This reduces the contingencies between processes in the target system, and this will reduce the sensitivity of designs of substructures to changes in the design of other substructures.

Koppenjan et al. (2011) point out that management of large engineering projects requires a capacity for rigorous planning and control as well as a capacity for flexible adaptation to changing conditions and that this leads to contradictory requirements for systems engineering methods. From a *predict-and-control* perspective, project management should focus on front-end analysis to produce precise definitions of project scope, tasks, schedules, and budgets that should be managed tightly through hierarchy and standardised information exchange. From a *prepare-and-commit* perspective, project management should define scope and tasks by setting global terms of reference, accepting that client needs and context will change, and focus on creating horizontal structures for cooperation and learning in the networks of client, team managers, contractors and technology providers.

Although systems engineering methodologies recognise the need for balance between the rigor and adaptiveness, the predict-and-control perspective tends to dominate over the prepare-and-commit perspective. This may be because this perspective is reflected and reinforced by systems engineering standards, such as ISO/IEC 15288 (systems engineering – systems lifecycle processes), which emphasize project management while providing limited coverage of early-stage activities of conceptualising the problem and considering alternative solutions (Kasser 2010). Interestingly, the review of systems engineering standards by Lowell (2009) shows that standards have been developed for specific aspects (quality, reliability, maintainability, producibility, safety; configuration management, parts management, environmental management), but not for (design for) the “ilities” associated with flux.

Meanwhile, the need to respond to contextual changes has led to the development of systems engineering methods that aim to enhance flexibility by speeding up the pace of the design and realisation phases. Examples are rapid prototyping (for software systems *RAD – Rapid Application Development*), the *Dynamic System Development Method*, the *Agile Software Process*, and *SCRUM*. These methods typically reduce the development time by combining lightweight project management, modular process structures, and incremental product delivery based on evolutionary development through many rapid iterations. Such iterative processes permit adaptation to flux but may hamper integration when engineering more complex systems.

Whether rigorous or adaptive, systems engineering methodologies can be seen as strategies for *managing* the flux that is inherent to large-scale systems engineering projects. This flux can be endogenous (design decisions and/or insights from validation and testing that change conditions for contingent design processes) as well as exogenous (changes in the context of the target system and/or changes in client needs and preferences). The management strategies are similar to those discussed in section “Strategies for Designing Artefacts in Systems that Are in Flux”. The stage gate decision points are institutional structures that function as “zipper stoppers” that should prevent “cascading failure” of a design, i.e., invalidation of the design of an entire subsystem when only one element or unit fails a test. Adaptable designs will reduce the risk of such failure or at least the time needed for redesign. Reconsidering the structural hierarchy (subsystem-unit-element) and the interfaces between subsystems may enhance flexibility. Flux mitigating strategies to reduce the need for redesign of system elements and units include enforcing standards and forward and backward compatibility of design and using client contracts to reduce “scope creep”.

All systems engineering methodologies have in common that they provide a generic structure or “architecture” that supports coordination of the multitude of concurrent design processes performed by a host of engineering professionals. Coordination of processes requires functional institutions. To improve the engineering practice, public authorities (“top-down”) as well as professional societies (“bottom-up”) seek to set standards for artefacts and their measures of performance, and protocols for their implementation. Koppenjan and Groenewegen (2005) offer several reasons why this is difficult. Firstly, most institutions that are not mere “rules on paper” but effectively shape social processes as “rules in use” (Ostrom 2005) are the result of informal and incremental processes. It is by such slow processes that institutions gain their legitimacy to constrain social interactions. Unless well embedded in “rules in use”, new rules lack this legitimacy, will not become institutionalised, and hence remain ineffective. These properties also explain why institutions (design strategies, systems engineering methodologies, best practices, modeling approaches, standards, policies) that have performed well in one engineering system cannot simply be “transplanted” to other engineering systems (De Jong 2004). Secondly, to fulfil their crucial role as suppliers of stability and predictability, institutions *should* be difficult to change. Being the “rules of the game” (Williamson 2000), they determine the chances for winning or losing, and players will attempt to change them to their own advantage. For this reason, purposefully designed institutional artefacts are typically designed for robustness so that it is not easy to adapt them.

In sum, attempts to create or change institutions can (and often should) be planned similar to (and often as part of) engineering interventions that focus on technical artefacts. By consequence, the capacity for planned intervention in engineering systems in flux depends on the capacity for institutional design.

Modeling for Design and Evaluation of Interventions in Dynamic Systems

Modeling is deeply embedded in engineering practice. Systems engineers use models for a wide range of purposes: analysis of the *system of interest*, design problem definition, conceptual design, requirements specification, testing, implementation planning and risk analysis, and many more. Overviews of modeling techniques and their application can be found in systems engineering handbooks (e.g., Parnell et al. 2011; Sage and Rouse 2009; Walden et al. 2015). The two types of application of computer-based models reviewed in this section relate more specifically to the strategies for design of interventions in engineering systems in flux reviewed in the preceding sections.

Exploratory Modeling

When it comes to modeling in support of design of robust, adaptive interventions that *satisfice* objectives and constraints over a wide range of futures, *exploratory modeling and analysis* (EMA) (Bankes 1993; Marchau et al. 2019) is the present state-of-the-art. Although the EMA terminology reflects that this approach was originally developed to support analysis and design of policies, EMA can be applied to any type of planned intervention. The general concept of (institutional) artefact as defined in section “Engineering Systems in Flux: Some Terminology” is virtually equivalent to the concept of policy as it is used in EMA. By extension, this also applies to implementation plans.

Similar to design strategies for flexibility and robust adaptive implementation plans (cf. section “Strategies for Designing Artefacts in Systems that Are in Flux”), the idea of adaptive policymaking is to plan in advance for policy changes that may be needed in response to future events. An adaptive policy prepares for additional actions (e.g., to seize opportunities or to cope with more stringent constraints) and defines variables (“signposts”) that should be monitored to see whether success conditions for the policy are still met or that adaptation is needed. Adaptability may be increased by adding “real options” that afford changes at relatively low cost. Ex ante analysis of opportunities and threats and timing and sequence of policy options produces a “roadmap” into the future. Using the graphical language of a metro map (see Fig. 2), such maps show for each option when (under some class of scenarios) it no longer meets the policy objectives (Haasnoot et al. 2013). These “adaptation tipping points” indicate the need for additional action and can be represented as crossroads that branch to options that are still feasible.

Keeping options open will reduce sensitivity to uncertain assumptions but comes at the cost of lower efficiency. Deep uncertainty prohibits appraisal of this trade-off using traditional expected utility methods (Lempert and Schlesinger 2000). Alternatively, the value of adaptability can be assessed using simulation models to explore *potential* system behaviors. Such “exploratory modeling” helps in specifying appropriate conditions for adapting a policy, by identifying actions and conditions that produce satisfactory results across a large ensemble of scenarios.

Figure 3 outlines the basic idea. The approach assumes that the analyst has a computational model that can simulate the dynamic behavior of the system. Given a

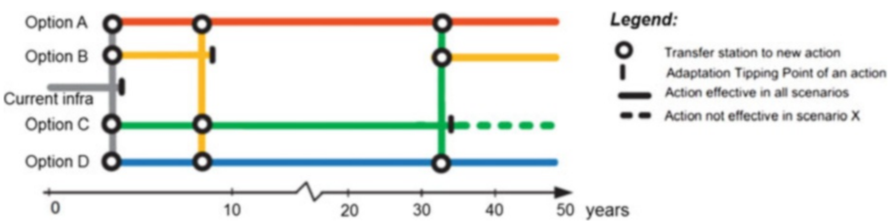

Fig. 2 Example of an adaptation pathways map. (Adapted from http://www.delta-alliance.org/toolboxoverview/dynamicadaptivepolicypathways)

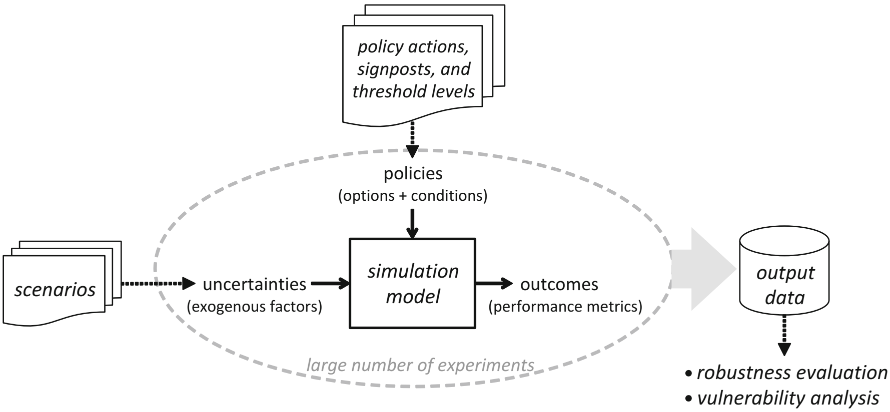

Fig. 3 Exploratory modeling

scenario (assumptions about uncertain exogenous factors in the future) and a policy (a set of policy options and conditional rules specifying when an option is applied) as input, the simulation produces outcomes (performance metrics that reflect how well the policy performed under the given scenario) as output. Repeating this experiment for a variety of policies and a wide range of scenarios (potentially many thousands) generates a large set of output data. These experiments and analyses can be performed efficiently using open source software tools (Kwakkel 2016). These tools support the generation and efficient (parallel) execution of computational experiments using existing simulation models and the visualisation and analysis of their results (identifying key uncertainties, assessing the efficacy of policy options, and iteratively improving the robustness of policies through vulnerability analysis).

Robustness evaluation searches for the policy that performed the best across all of the scenarios, while vulnerability analysis seeks to identify the scenarios in which a particular policy performs poorly, so that policymakers can think of actions that will protect the policy from failing. Robustness can be evaluated using "regret" as measure, where regret is defined as the difference between (a) the performance of a policy in a given scenario and (b) the performance of the best policy in that scenario. The examples in Fig. 4 illustrate (for only a small, two-dimensional scenario space) the regret matrix for three alternative policies, demonstrating that the adaptive policy C is much more robust than the static policies A and B.

Exploratory modeling can support "design for robustness" as well as "design for flexibility" strategies as reviewed in section "Strategies for Designing Artefacts in Systems that Are in Flux" because it provides well-defined quantitative procedures to evaluate the lifecycle performance of a design. Recent developments involving the use of algorithms for multi-objective robust optimisation (Hamarat et al. 2014; Beh et al. 2017) will afford using EMA also for more directed search for interventions that will be effective in an uncertain dynamic context.

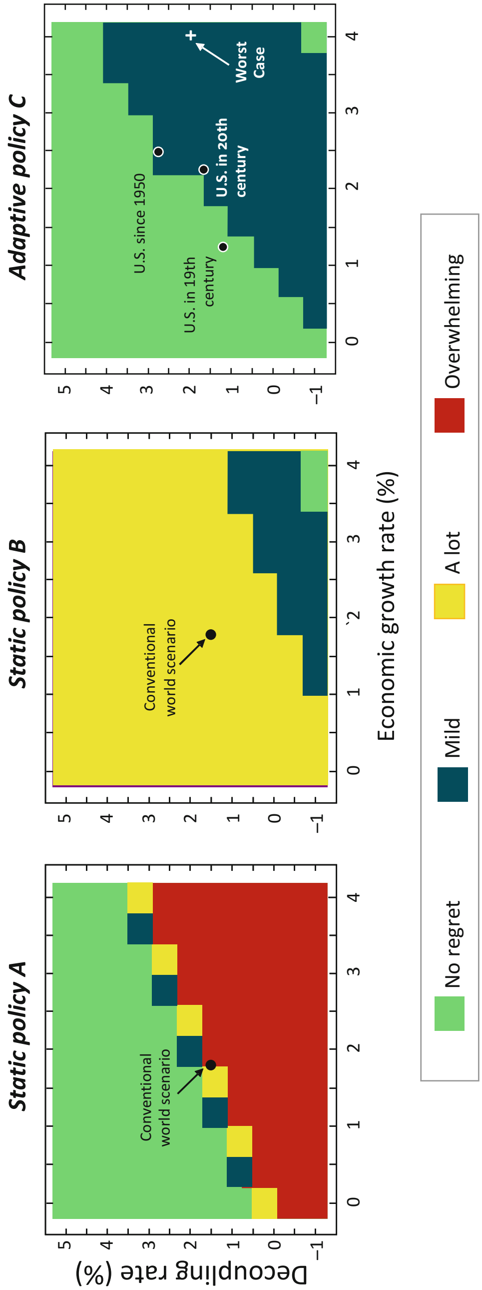

Fig. 4 Robustness evaluation of 3 policies under 121 scenarios. Adapted from Lempert (2004)

Participatory Modeling

Engineering systems comprise technical-physical elements as well as cognitive social actors who are capable of acting and reacting with strategies to the patterns they help create. This adds a layer of complexity not experienced in the natural sciences (Lansing 2003). Agent-based models can capture some of the non-linear effects of socio-technical systems that would otherwise be out of reach. However, computational models have a fundamental limitation because they lack the capacity of humans for "double loop learning", i.e., for reinterpreting their environment, reframing their problems, and developing novel strategies (Argyris 1976).

Recent advances in computation power, visualisation, and human-computer interaction provide new possibilities to make humans (typically representatives of the client) an integral part of an advanced simulation-game model (Mayer 2009; Meijer 2012). Part of the complexity of the system can be modeled and simulated in the computer, while significant dimensions of strategic actor behavior and learning are captured in a social-interactive game. Because they can reveal reinterpretation and alternative uses of artefacts (both technical and institutional), simulations with models of this type afford more realistic ex ante evaluation of engineering interventions. Moreover, directly involving users in modeling activities in early stages of the systems engineering process can improve elicitation of design requirements as well as enrich the set of design concepts.

Similar to exploratory modeling, participatory modeling has its roots in policy development (Pahl-Wostl 2002; Barreteau 2003), but the approach is gaining terrain in support of systems engineering activities (Daniell 2012; Nolte and Herrmann 2016). Where the application of exploratory modeling is mainly limited by the availability of computational resources, the main challenge for participatory modeling lies in organising and managing the process.

Conclusion

Engineering systems are in perpetual flux. While performing countless functions – day to day, minute to minute, or even on millisecond scale – that provide food, shelter, transport, and telecommunication and permit trade and social interaction, these systems evolve over the years as engineers seek to better meet human needs using new technologies. Designing and performing interventions in such intricate and dynamic systems is in many ways similar to trying to fix an engine while it is running. Although at first glance such endeavour would seem absurd, it need not be, provided that the engineers know what they are doing. After removing the right cover plates, a leaking fuel line can be patched. If the engine has more than one cylinder, a sparkplug can be replaced without stopping it, especially when the engine was designed to run on a variable number of cylinders and allow for controlled disabling. And if the engineers know how to keep the larger system of which the engine is part functioning reasonably well without propulsion, they can still opt to shut it down for some time. Engineers fixing a twin-engine airplane in mid-flight would definitely be spectacular, but voyage repairs on ships at sea are not uncommon. The key to success is knowledge, skill, and a sound plan.

Understanding what such a plan entails and how it can be devised has been the focus of this chapter. When planning an intervention in an engineering system, engineers cope with flux by aiming for robustness, flexibility, and evolvability of their designs while seeking to mitigate flux in the immediate context of their intervention. Each aim calls for particular strategies. These strategies have formed the silver thread for this chapter, as they can be applied to all aspects of design: the artefact (the object that engineers intend to introduce or modify by their intervention), the implementation plan (the organisation in time and space of the intervention and the required resources), as well as the systems engineering methodology (the organisation of the design process through procedures and standards).

Planning entails anticipating future conditions that result from planned actions as well as exogenous changes. Today's massive computational resources allow engineers to test the robustness and flexibility of artefacts as well as their implementation plans by simulating their performance under a vast range of scenarios. Datamining of the simulation results can reveal vulnerabilities that can be remedied by, for example, introducing reconfigurable components or preparing for alternative adaptation paths. To overcome the limitations of computer models as means for anticipating human behavior and social response, engineers have started to directly involve future users and other stakeholders in their simulations. Large-scale simulations based on participatory modeling and serious games may soon become mainstream in systems engineering projects.

That processes of design, implementation, and use of artefacts are entwined is inherent to engineering practice and goes back to prehistoric times. What has changed is the scale and the interconnectivity and hence the complexity and flux of engineering systems. As these continue to grow, so will the challenge of gathering knowledge, acquiring skill, and devising a sound plan so as to make successful interventions. The engineering principles and strategies reviewed in this chapter provide guidance on how to meet this challenge.

Cross-References

- ► Choosing Effective Means: Awareness of Bias in the Selection of Methods and Tools
- ► Engineering Systems Interventions in Practice: Cases from Healthcare and Transport
- ► Evaluating Engineering Systems Interventions
- ► Flexibility and Real Options in Engineering Systems Design
- ► Risk, Uncertainty, and Ignorance in Engineering Systems Design
- ► The Evolution of Complex Engineering Systems

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22 Engineering Systems Integration, Testing, and Validation

Ricardo Valerdi and Brendan P. Sullivan

Contents

R. Valerdi (✉)
Department of Systems & Industrial Engineering, University of Arizona, Tucson, AZ, USA
e-mail: rvalerdi@arizona.edu

B. P. Sullivan
Department of Design, Production and Management, University of Twente, Enschede, Netherlands
e-mail: b.p.sullivan@utwente.nl

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Abstract

Developing and implementing interventions in engineering systems must undergo rigorous testing before being deployed into their operational environment. An engineering system's complexity determines the sophistication of the testing needed to demonstrate its ability to meet intended objectives. In this chapter, we explore the various testing methodologies that shed light on the behaviour of a system. This section introduces the reader to the general role of life cycle cost of systems in testing, including reference engineering systems that can leverage such a testing approach. Within section "Engineering Systems Considerations and Interventions", the implications of various types of system complexity are presented along with the implications that tight and loose coupling can have on systems. This section includes an example taken from the International Space Station that illustrates various considerations involved with testing engineering systems. Section "Testing Methodologies" discusses the finer details of systems testing by presenting current challenges for testing engineering systems, suitable testing approaches, and the roll of test planning (design of experiments) in engineering systems development. Section "Developments in Testing" of this chapter presents an example of a drone delivery system that leverages a decision support system to help optimise test strategies in situations where the system is too complex to test manually, and trade-offs must be made between test coverage, cost, and delivery time. At the heart of the methodology presented in this section is an algorithm that can help lead to smarter testing decisions through the prioritisation and sequencing of tests. This is accomplished by integrating a parametric cost model, knowledge gradient algorithm, and Bayesian updating algorithm. The chapter aims to support systems engineers coordinate and plan tests that help decision-makers learn as much about a system as quickly as possible while gaining confidence that the system is ready for deployment.

Keywords

Complexity · Coupling · Engineering systems · Grand challenges · Life cycle · Testing · Validation · Verification

Introduction

Systems design is the organised and structured application of processes that result in the development, production, deployment, training, operation and maintenance, refinement, and retirement of a system (Rasmussen 2003). The end goal is to develop systems that deliver value for stakeholders by fulfilling requirements, ensuring effective interfaces, and validating specific system objects on time and cost. The engineering of systems provides and allows for both creative design alternatives for meeting system objectives on paper and technical competence to ensure these objectives are also delivered in real life. This is achieved through the design of components, configuration items and integration, across the entire life cycle of the system. Systems can be described according to their purpose/objectives, complexity, social dimension, and technical elements, namely:

- **System**: is a construct or collection of different elements (interacting components) that together produce results not obtainable by the elements alone (Blanchard 2004).
- **System Task/Function**: An action, a task, or an activity performed to achieve a desired outcome (Hitchins 2007).
- **Complex Sociotechnical Systems:** are complex purpose-built systems composed of numerous interconnections, interactions, or interdependencies between social, managerial, and technical elements that are difficult to describe, understand, predict, manage, design, and/or change (Cherns 1976).

When designing engineering systems, it is necessary to consider the technical and social complexities brought upon by the needs being met and the critical functions required to meet those needs. To support this, the chapter focuses on the role, methods, and value of testing. We consider various testing approaches and techniques that help bring engineering systems to life. Given the current challenges in testing complex engineering systems, we highlight an approach that considers uncertainty, value-based decision-making, and cost that jointly can help bring increase our understanding of system behaviour in a short amount of time.

Sociotechnical Systems Theory

According to Cherns (1976), sociotechnical systems are systems in which both human and non-human elements interact to deliver societal value in some way. This is one of many possible ways to describe engineering systems. In order for any engineering systems to be achieved, societal (people) and technical aspects must be considered and effectively organised to improve how we interact, interconnect, and collaborate.

Sociotechnical systems theory has many connotations and applications ranging from engineering to management and education, the commonality between all disciplines being the interaction between social and technical factors that characterise the successfulness of system development (Emery and Trist 1960; Trist 1981; Baxter and Sommerville 2011). Introduced in section "Sociotechnical Systems Theory", the grand challenges facing the world require an integrative holistic view of large-scale, complex, technologically enabled systems designed with a sociotechnical perspective.

Examples of sociotechnical systems can range from energy distribution systems that distribute mixed energy (solar, wind, hydro, and non-renewable) across a grid network to an intermodal transportation system where rail, commercial vehicles, maritime, or air transportation come together (see Fig. 1) to provide a valuable service for society. In developing and considering such sociotechnical systems, it is

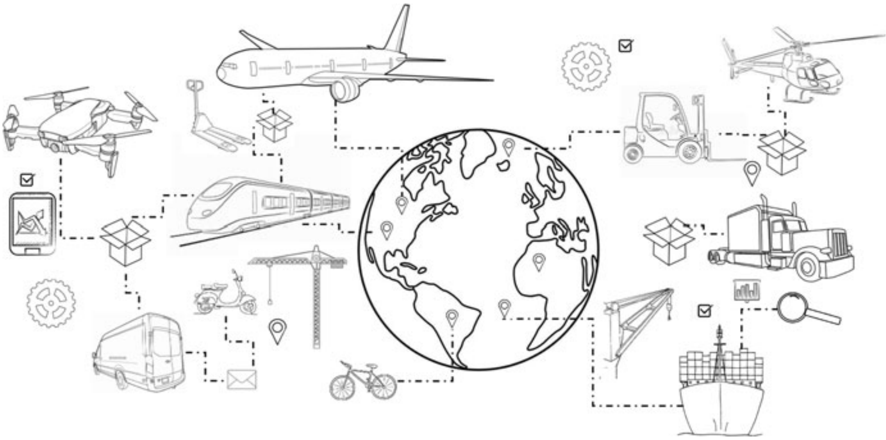

Fig. 1 Intermodal system – improving infrastructure

essential to realise that decisions should be made to set up the possibility for future innovation and forward-thinking solutions, which can be done by carefully considering and evaluating the implications of different decision scenarios on the system across multiple points of time.

Beyond Cherns, additional aspects of sociotechnical systems are proposed by Clegg (2000):

1. The interaction between social and technical factors supports the successful (or unsuccessful) performance of a system.
2. Purposeful and goal-directed functions that deliver value to society in some way.
3. Interrelated, with strong dependencies that allow each aspect to complement and benefit the other enabling collective improvement and optimisation.

According to Cherns (1976) and Clegg (2000), sociotechnical systems utilise multifunctional, multilevel, multidisciplinary teams to develop systems that are capable of delivering societal value in an interconnected and collaborative manner. By considering:

- Compatibility – Process/function is compatible with objectives.
- Minimal critical specification – Specify no more than what is necessary, while always specifying what is essential.
- Variance within the system – Any unplanned/unprogrammed event, which creates deviation in quality, responsiveness, and function.
- Multifunctional parts/components – Institution of choices that can perform functions or meet the systems objectives by using combinations of elements.

(continued)

- Boundaries – Multidimensional clusters that operate to support the distribution of work rather than consolidated groupings.
- Information flow – Deliverance and generation of information/data where it is needed, and in the format desired and according to the necessary and specified context (correct information, for the correct person/system, at the correct time).
- Support congruence – The system should support and reinforce social principles.
- Design and human values – Provide quality system solutions without limiting or suppressing the values of those the system was built to benefit.
- Inherent incompleteness of the system – Recognition that upon completion and deployment of the system, its consequences will necessitate redesign.

The design of sociotechnical systems considers the aspects previously discussed while also considering the objectives that the overall system is trying to achieve. This requires that the social and technical elements provide for and support the innovativeness of the people involved to identify and establish goals that can be attained through interrelated optimisation. This includes, but is not limited to, how machines and technical systems behave and how people interact with them to bring external forces (political, ecological, and societal) into the design process. This interaction between each of these forces impacts the inherent complexity of the system by considering compatibility, minimal critical specification, variance within the system, multifunctional parts/components, boundaries, information flow, support congruence, design and human values, as well as the inherent incompleteness of the system. For example, it may not be as simple as testing to make sure a system meets the end user's needs. The impact of the system on its owners, operators, government regulators, taxpayers, and competitors may very well be as crucial as the agreed-upon technical requirements between client and developer. Consider the social and political implications of electric vehicles as an example of the broad and far-reaching implications that extend beyond the manufacturer and driver relationship. This highlights the complexities involved in testing and evaluating the performance of engineering systems during their design phase, instead of simply observing (and most likely criticising) it during its operational life.

US National Academy of Engineering Grand Challenges

There are many types of engineering systems developed to overcome challenges on a global and individual level. In considering design, engineering systems are generally forward-thinking solutions that solve problems related to humanity, ranging from the exploration of space and planetary science, sustainability, health, security, and general human need. The purpose for engineering systems in each of the facets of life differ, though irrespective of their addressed facet, a deep understanding of the problem being addressed improves deciding which functions are better and what the is best way to test such functions. Table 1 provides an overview of systems and explorative solutions that have been developed or are under development according to the United State National Academy of Engineering Grand Challenges (2021).

For the systems and solutions introduced in Table 1 to be successfully developed, accompanying testing strategies must be considered early in the life cycle. For testing to inform decision-making, the testability of such systems has to be treated with the same importance as other attributes like reliability, interoperability, sustainability, and survivability. Testing considerations grow in importance as systems grow

Table 1 US National Academy of Engineering Grand Challenges (2021)

Challenge	Explorative solutions and systems
Making solar energy more economical	Development of future generation hybrid solar cells with organic semiconductors and inorganic nanostructures Solar-powered aircraft – Solar Impulse (2016), Airbus Zephyr S HAPS (2018), Boeing Odysseus (2019)
Provide energy from fusion	Joint European torus (JET) and the mega amp spherical tokamak (MAST) in the United Kingdom International Thermonuclear Experimental Reactor (ITER), currently under construction in Cadarache, France (2020)
Carbon sequestration methods	Sleipner A project Climeworks direct carbon capture plant (Switzerland)
Manage the nitrogen cycle	Solar glass Smart fertilisers
Provide access to clean water	Desalination Water reclamation Smart irrigation
Restore and improve urban infrastructure	Intermodal transportation systems Smart grids
Advance health informatics	Remote patient monitoring Electronic medical records Master patient index
Engineer better medicines	Rapid diagnostic systems Personalised medicine (theranostics)
Reverse engineer the brain	Artificial intelligence Neural prostheses
Prevent nuclear terror	Passive nuclear material monitoring Nuclear screening systems (e.g. nuclear car wash)
Secure cyberspace	Self-healing computer systems Cyber-attack-resilient architecture for next-generation electricity distribution systems
Enhance virtual reality	Augmented and virtual cognitive systems
Advance personalised learning	Evolutionary educational presentation systems Educational recommender systems
Engineer the tools of scientific discovery	NASA space launch system OSIRIS-REx Mission

in complexity because the more uncertainty there is about a system's performance, the more we must invest in ensuring that it is ready for deployment (DoD 2004; Potts et al. 2020). Test results are also crucial in the early-stage exploration of the problem and solution space, giving decision-makers a chance to (re-)evaluate the feasibility and associated costs of alternative solutions.

The Role of Life Cycle Cost of Systems in Testing

Every human-designed engineering system has a life cycle and cost. The life cycle cost (LCC) of an engineering system is the total cost over its entire life span, including development, verification, testing, validation, and disposal (Mooz et al. 2003). Despite every engineering system (product or solution) having a cost, there historically has been an emphasis by engineers to focus on the performance of a system with less regard for the downstream costs.

> LCC is the total cost of all costs related to or associated with a system from cradle to grave (development, verification, testing, validation, and disposal) and explicitly accounts for the time value of money (the variation in the cost of an expenditure relative to its timing).

LCC is used to quantify the costs associated with an engineering system throughout each phase of its anticipated life. It supports the selection of economically viable and innovative solutions while ensuring that all aspects of the system integrate and function according to the requirements and needs of the stakeholders. Through this economic approach, LCC supports decision-makers to identify and choose the cost-effective approach from a series of alternatives to deliver the greatest value to the stakeholder at the lowest long-term cost (Farr 2012).

LCC can be a valuable tool used for systems decision-making (passing between decision gates). As shown below, the general system life cycle consists of five stages: conceptualisation, design, development, production and testing, and operation and retirement of the system (disposal). Each of the life cycle phases has costs and must be carefully considered since the consequences of making early decisions without accurate analysis can dramatically impact the percentage of system costs against time required for development. Considering Fig. 2, we can infer that by the production and testing phase of a new system, 50% of the total LCC has been spent, while 95% of the funds have been committed based upon decisions made by the developer or client. The cost to extract defects represents the cost associated with fixing unanticipated problems. The later the defect occurs, the more costly it becomes to rectify it.

LCC estimates are built upon the projections of total cost to the funding organisation for the system ownership and acquisition over its entire life span. This may include the costs of the direct, indirect, recurring, non-recurring, and other related

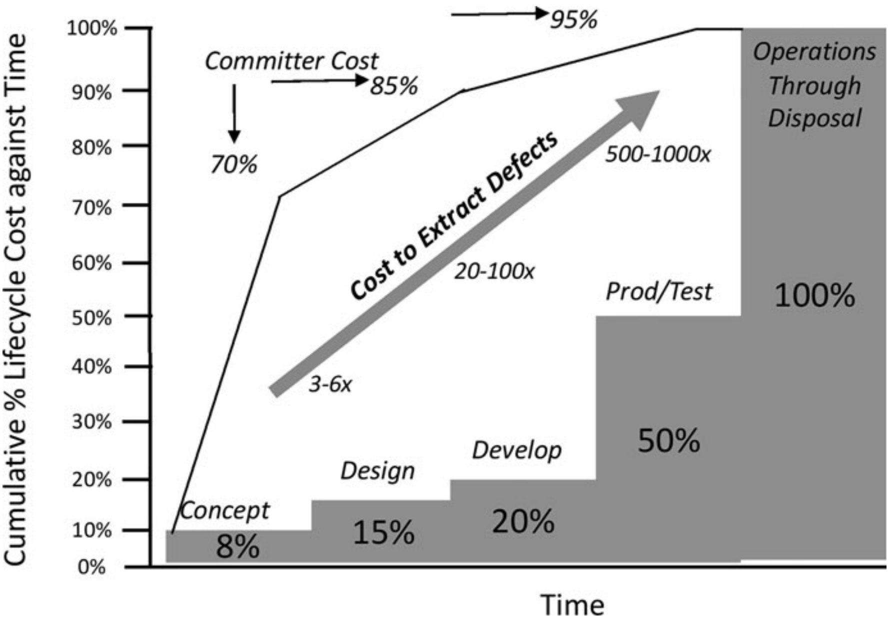

Fig. 2 Committed life cycle cost against time (INCOSE 2015)

costs incurred or estimated to be incurred during the design, such as research and development, investment, operations, maintenance, support, disposal, and other relevant costs. It is essential to consider the phases of LCC, because the upfront acquisition phase is only a small part in relation to the total cost. Yet it plays a significant role in the decisions made that will have downstream effects (DOD 1983; Farr 2010; Kerzner 2017).

Testing therefore also has to include testing the validity of life cycle cost estimates, as well as generate the necessary knowledge to improve the accuracy of life cycle cost estimates.

Engineering Systems Considerations and Interventions

When designing engineering systems, it is necessary to consider the technical and social complexities brought upon by the needs being met and the critical functions required to meet those needs. When referring to large-scale, sociotechnical engineering systems design, these systems are always partially designed and partially evolved (de Weck et al. 2011). Practically, that means we will primarily look at interventions in existing systems rather than a complete redesign. This presents an even more complicated scenario because not all decisions can be made in the interest of optimal systems design. Some decisions, large and small, are already hard-wired due to constraints that result from previously existing infrastructure, culture, or processes.

A system is only as good as the tests imposed to it, and a test can be good only if you can clearly understand the numerous interconnections, interactions, or interdependencies that you will be analysing. To do this, we must consider the trade-offs between requirements, functions, and alternate system resources that have/will take place to achieve a valuable, cost-effective, life cycle balanced system that maximises stakeholder desires (Blanchard et al. 1990). The following best practices synthesise several considerations that support the eventual goal of delivering a successful system (Bartolomei et al. 2011).

- Clearly articulated problem definition, stakeholders (and relationships), system mission, and environment
- Definition of the problem including context and external systems, the system must interact or interface with
- Balancing of needs between stakeholders and engineering, throughout development (communication), including the articulation of system needs, and translation of requirements
- Matching trade-offs, to make requirements more transparent and support the identification of requirements that are not feasible
- Articulation of critical functions and relationships to the user (human-robot interaction, cost, complexity, risk to human life, etc.)
- Testing plan to mitigate risk before deployment

Complexity in Sociotechnical Systems

All systems have some inherent level of complexity, but the formation and magnitude of their complexity differ. It is essential to understand how complexity impacts design and by connection how it impacts its testing. It is therefore necessary to consider both technical and human complexity when working with an engineering system.

Contemporary technology-centric systems are diverse and contain higher degrees of systems complexity than ever before, requiring more knowledge than ever before to understand the operational functions and goals of the systems (Philbin 2008). Yet, the dimension of complexity may be overlooked, not fully understood, and often underestimated within systems design and development processes. Thus, as technologies advance and the magnitude of systems effort intensifies, systems complexities and uncertainties increase simultaneously (NASA 2007).

To focus the conversation, it is helpful to determine the types of complexities present in engineering systems and their influence on cost throughout the life cycle. McShea (1996) suggests that understanding the nature and state of complexity is a complex subject matter itself, regardless of the types or origins that a particular type of complexity may reside within a system. Recognising this challenge, Sheard (2013) identified four entities prevalent in complex engineering systems.

Complexity types (per Sheard 2013):

- **Project**-related complexity represents complexity types the organization developing the system. This is considered since the organization performing the work is generally already in existence and therefore has people already in place who work with others and is responsible for allocating responsibility for product realization tasks.
- **System**-related complexity refers to technological considerations and how the system is composed. This is the most commonly thought of complexity.
- **Environment**-related complexity refers to the ‘Way Things Are’ and can extend to include both external factors and stakeholders. Which identify/ determine other systems that the system being developed must interface with as well as the technological environment.
- **Cognition**-related complexity emphasises the human aspect through the consideration of individual limitations and the actions in place to reduce risk and uncertainty.

Considering such complexity allows for the reduction and/or better management of potentially detremental impacts that can effect test efficiency and system success. As described in section “Example: International Space Station” project complexities can have direct implications on the cost, overrun, and scheduling of development, system type complexities that reflect the *number of systems to be integrate and the number of interfaces that can increase the complexity of tests required to be performed (it is critical that test plans* minimise redundancy and maximise test efficiency). Moving beyond complexity, it is imperative to clearly define the boundaries of the system itself in order to determine how it will be tested.

System Boundaries

System boundaries are a fundamental part of engineering systems. The purpose of boundaries is to develop conceptual separation between the important elements of the system (relevant component) and its environment (external elements that can affect or be affected by the system). Engineering systems are bounded by component limits of control and are aligned with the system’s purpose. Drawing the boundary correctly is crucial to systems design, development, and testing because to solve a systems problem, you must first know what the system is.

Context is understood as everything beyond the system’s boundary. This includes the environment and the source for inputs and the later destination for system outputs. The context affects the general nature of the inputs and interpretation of the systems outputs, and stakeholders need to be cognisant of contexts that can affect the system. Since the context and, by extension, the environment are outside of the system and cannot be controlled, it causes uncertainty for the developers.

In the case of an engineering system, the boundaries and internal interfaces can be documented in multiple ways, including through either interface control document or interface control specification. The importance of understanding interfaces concerning system boundaries is that stakeholders must understand the assemblage of the system, the functions, and capabilities for the development to be successful. Through this understanding, combined interactions, including processes and data flow, within and across the system facilitate the modelling and evaluation of system behaviour and performance to better understand and plan testing.

Useful lexicon for understanding boundaries in engineering systems

- Boundary: separates the system's internal elements and processes, from external factors or elements.
- Context: defines the development and operational space outside of the system boundary, illustrating the interaction between elements.
- Environment: exogenous factors or elements that affect or can be affected by the engineering system (internal factors and elements).
- System: is a construct or collection of different elements (interacting components) that together produce results not obtainable by the elements alone. Can be understood as a group of components that interact together and are necessary for fulfilling a purpose.
- Subsystem: is a system in its own right, except it normally will not provide a useful function on its own, it must be integrated with other subsystems (or systems) to make a system.
- Elements: are not restricted to hardware but can also include software and can even include people, facilities, policies, documents, and databases.
- Component: are elements that make up a subsystem or system and are dependent on other components (interact with each other) to create the system's behavior.

Demystifying Integration through Coupling

Another dimension that is important in understanding engineering systems complexity and testing is coupling (Marais et al. 2004). That is, how connected an engineering system's parts are to each other. The degree of coupling within an engineering system may be described across a range of tight coupling to loose coupling. Tight coupling is when components are highly dependent on one another, while loose coupling is when there is little or no dependency between components. As shown in Fig. 3, the differences between tight and loose coupling can also be described in terms of coordination and information flow.

The decision about the degree of coupling in an engineering system may be driven by architectural attributes like quality, security, flexibility, interoperability, reliability, performance, and many others (Elias and Jain 2017). For instance, to maintain high levels of security, an engineering system might be loosely coupled to

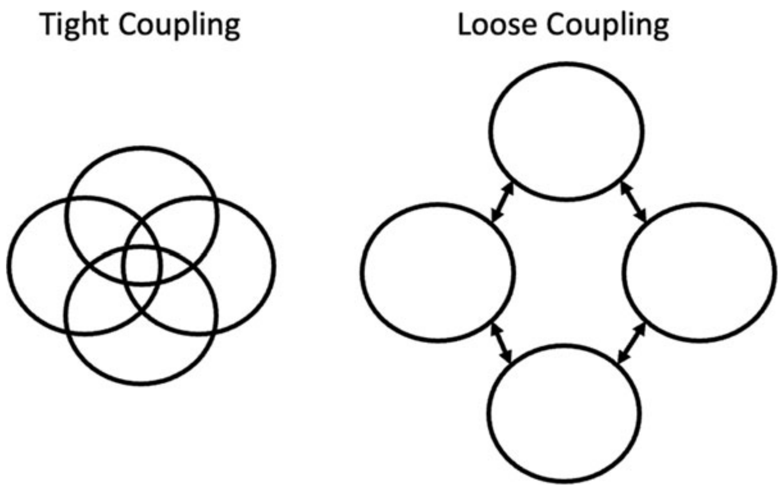

Fig. 3 Tight vs. Loose Coupling

create isolation between system components in the event one of them is breached. In some cases, the degree of coupling may not be negotiable because of legacy considerations. Many engineering systems have inherited traits that are unchangeable and therefore decrease the number of solutions that can be implemented to meet their objectives.

In either case, the degree of coupling significantly impacts the testing of engineering systems. In loosely coupled cases, more tests may be required to ensure the functionality is adequately working. In tightly coupled cases, however, higher connectivity may be an advantage because it might require less tests to observe the system's behaviour.

As always, there are exceptions to these examples. For instance, tightly coupled systems may require all of the components to be available and engaged in the test. This may not be a simple or inexpensive task. Similarly, loosely coupled systems may be simpler to test by undergoing testing at different times and locations, facilitating coordination and data collection.

Example: International Space Station

The International Space Station (ISS) is one of the largest and most complex engineering systems, developed out of a collaborative effort between the United States and Russia to provide for an on-orbit habitable laboratory for scientific and research activities (International-Space-Station-Program-Science-Forum 2015). Stockman et al. (2010) provide a detailed case study of the ISS from the systems engineering perspective. The complexity of the system can be seen throughout the development process taking form in the system, the environment, cognition, and more specifically in project (section "Complexity in Sociotechnical Systems"). The project complexity was related to many elements, but none so significant as the inclusion six international partners that were tasked to collaborate in the building of 87 flight elements integrated over 44 assembly flights during a 5-year time frame. Although both the National Aeronautics and Space Administration (NASA) and the Roscosmos State Corporation for Space Activities had significant experience in multi-national complex space system development, the partnership and integration required to develop the ISS was overwhelming, leading to project delays, overruns, and integration issues (Thomas 1996).

Complexities within the ISS:

- **Project** – multiple space agencies involved in building the technical system; NASA (United States) and ROSCOSMOS (Russia)
- **Technical System** – Systems being designed; ISS Vehicle, ISS Flight Elements, ISS Launch Package
- **Environment** – the technological environment of ISS stakeholders, and the technological environment into which the system will be inserted when built.
- **Cognition** – Varying approaches to system engineering, design, and development (NASA and ROSCOSMOS)

As a sociotechnical system, the ISS can be further described through the multifunctional, multilevel, multidisciplinary international teams used to develop the engineering system and the critical societal value derived from the research and experiments performed. According to the International Space Station Program Science Forum (2015), the research performed on the ISS to benefit humanity includes the following:

- Development of health technology
- Solutions to prevent bone loss
- Human immune system defences
- Medical treatments and therapies
- Food and the environment
- Heart health and biorhythms
- Improving balance and movement

Many boundaries existed in the development; however, two observable and critical areas of emphasis delineating internal process from other system elements (section "System Boundaries") were the (1) Vehicle Systems Engineering & Integration (SE&I), the SE&I of the of all the flight elements of ISS Vehicle with each other, and (2) Launch Package SE&I, the SE&I of the individual ISS Vehicle flight elements with the other constituents of an assembly mission, such as launch vehicle integration. The ISS was designed as a network of distributed subsystems that were

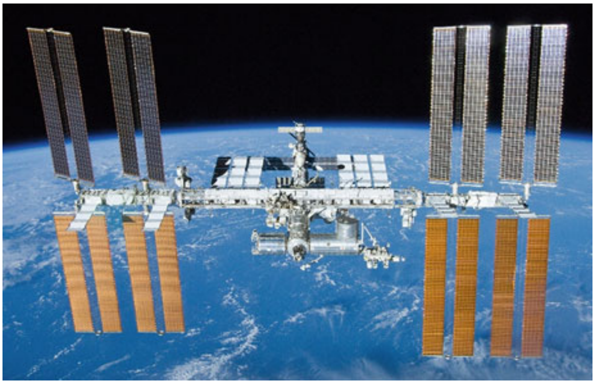

Fig. 4 International Space Station (NASA – public domain image)

interconnected among discrete elements (section "Demystifying Integration through Coupling"). Each subsystem and element introduced unique design and integration challenges independently, though for the ISS to be physically interconnected and functionally interoperable, the distributed systems and discrete elements also needed to be integrated seamlessly into a unified space vehicle (Stockman et al. 2010). This integration concept made the planning and execution of testing for the ISS both difficult and complex since during building each flight element, the subsystem teams would develop their subsystems to meet the respective performance requirements during each stage of the ISS Vehicle assembly (see Fig. 4).

The integrated performance of all subsystems at each stage of the ISS Vehicle assembly mutually determined mission success (Stockman et al. 2010).

Testing during the development of the ISS presented a major challenge to the NASA and its partners Stockman et al. 2010. Despite the ISS Program verification philosophy to "integrate and test on the ground what we fly before we fly", new and innovative methods to test and verify interfaces were required. Reasons for this were attributed to many of the modules being developed in different countries and delivered "just in time" for the launch, leaving minimal time for integration testing. Therefore, before deployment, each module had to be tested for its own internal operation. Then it had to interface with the launch vehicle, and finally, it had to work in space while integrated with multiple modules and systems (Stockman et al. 2010). Even if an individual module performed well by itself, the success of the ISS depended on the ability of all modules to perform well as an integrated whole.

We now shift our attention from describing the complexities of engineering systems to exploring specific methodologies that can aid in successful testing.

Testing Methodologies

Before discussing specific methods and their application domain, it is beneficial to begin by defining commonly used terminology in the testing context, particularly when working in a multifunctional, multilevel, or multidisciplinary team. This common vernacular ensures conformity throughout the testing process and should be applied to all testing methods. It is likely impossible to test for every imaginable scenario, due to complexity or cost (Barhorst et al. 2011). The objective of the test should therefore be well defined and correspond to the capabilities of the selected method. Vague or open-ended verification and validation plans lead to project overruns, system failure, and loss of confidence from the stakeholders (Wheatcraft 2012).

The terms *validation* and *verification* are sometimes confused and frequently mentioned in the incorrect order (e.g. verification and validation) (Ryan and Wheatcraft 2012). On the one hand, validation, which should be listed first, is the process of evaluating the final product to check whether it meets the customer expectations and requirements. In other words, it is the process of checking "Did I build the right system?"

On the other hand, verification is the process of testing documents, design, and functionality. It includes activities such as inspection (measurement to verify that the item conforms to its specified requirements), analysis (the use of established technical or mathematical models or simulations, algorithms, or other scientific principles and procedures to provide evidence that the item meets its stated requirements), and demonstration (actual operation of an item to provide evidence that it accomplishes the required functions under specific scenarios). In other words, it is the process of checking "Did I build the system right?". The order in which these are done is important because verification might be successful, but for a system that is the wrong thing for the client (it was not validated). That is why validation needs to occur before verification.

Challenges for Testing Engineering Systems

Engineering systems offer a unique opportunity for optimising testing because of their distributed nature, emergent properties, and dynamic topologies and boundaries. A key challenge is that additional capabilities can be gradually inserted in a system or environment and each insertion requires extensive testing before being deployed successfully in operational environments. This challenge can be addressed through systematic planning that leverages techniques from the "science of testing" that helps identify nearly optimal solutions that minimise cost while maximising test coverage (Young 2011). However, such a task is nontrivial because of the unstructured and dynamic environment of engineering systems. To address this challenge, we propose an innovative testing approach that blends techniques such as parametric cost modelling, knowledge gradient algorithms, and Bayesian updating algorithms.

These analytical techniques can help manage the delicate balance between performance, resiliency, and security level (Yang et al. 2012). The trade space illustration in Fig. 5 involves the selection of feasible solutions (dots) that meet or exceed the desired performance threshold (dashed line).

Even when feasible solutions are identified (dots), external considerations – such as government policy or political opposition – may still eliminate them from consideration. This is why the sociotechnical system approach may be helpful in comparing solutions from a broader, more holistic perspective.

Fig. 5 Tradespace for engineering systems

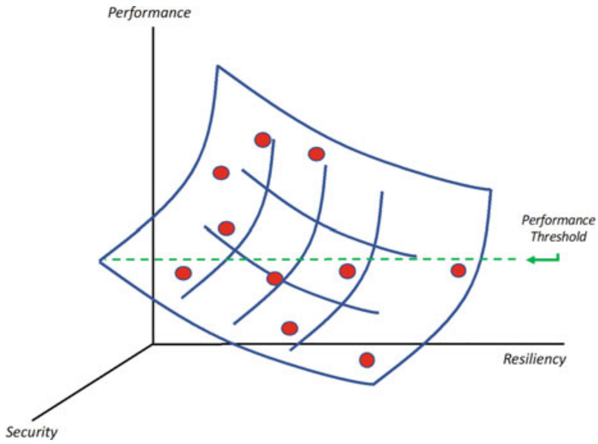

Table 2 Different types of testing

Functional testing types	Non-functional testing types
Unit testing	Performance testing
Integration testing	Load testing
System testing	Stress testing
Sanity testing	Volume testing
Smoke testing	Security testing
Interface testing	Compatibility testing
Regression testing	Install testing
Beta/acceptance testing	Recovery testing
	Reliability testing
	Usability testing
	Compliance testing
	Localisation testing

Testing Approaches

Together, validation and verification are part of the broader concept of testing. There are many types of testing approaches, each with their advantages and disadvantages. The most common testing types, in Table 2, are categorised as functional and non-functional testing according to system performance type being verified.

Functional testing ignores the internal parts and focuses on the output to check whether intended requirements are met. It is a black box-type testing geared to the functional requirements of a system (Myers 2011; Meinke 2004). Non-functional testing involves testing the "how" (non-functional requirements) a system will accomplish something and can be accomplished by implementing unique tests which are presented in Table 2, including load testing, stress testing, security, volume, recovery testing, etc. (Hooda and Chhillar 2015). The objective is to ensure whether the response time of a product is quick enough to meet the requirements.

Beyond the testing types described above, other broader approaches should be noted. Alpha testing aims to identify all possible issues or defects before releasing it into the market or to the user. Beta testing is a formal type of testing that the developer or the customer may carry out. It is performed in the real environment before releasing the product to the market for the actual end users.

Happy path testing aims to test an application successfully on a positive flow (Cohen et al. 2005). It does not look for negative or error conditions. The focus is only on the valid and positive inputs through which application generates the expected output. Negative testing employs the mindset of “attitude to break”. It involves using incorrect data or invalid data or input. It validates that if the system provides an error or invalid input, it will behave as expected.

In risk-based testing, the functionalities or requirements are tested based on their priority (Amland 2000; Felderer and Schieferdecker 2014). Risk-based testing includes testing of highly critical functionality, which has the highest impact on business and in which the probability of failure is very high.

Exploratory testing is informal testing performed by the testing team. The objective is to explore the functionality and find existing defects (Itkonen and Rautiainen 2005; Itkonen et al. 2009). Sometimes it may happen that during this testing, a major defect is discovered that causes a system failure.

Acceptance testing is performed jointly between developer and client to verify whether the end to end flow of the system is as per the business requirements or not, and if it is as per the needs of the end user (Davis and Venkatesh 2004). This may involve both functional and non-functional testing. The client accepts the product only when all the features and functionalities work as expected.

Regardless of which test methodology is employed, there are a variety of measures of effectiveness to evaluate their usefulness. These include speed, fidelity, knowledge obtained, coverage, accuracy, risk reduction, and cost savings. Ultimately, testing should increase confidence that helps stakeholders decide whether a system is ready to be deployed into its operational environment.

Design of Experiments

A recent trend in testing has emphasised statistical methods for more efficient use of resources (Cohen et al. 1998). This is motivated by decreased testing budgets, more complex systems, more software-intensive systems, more upgrades to existing systems (i.e. evolutionary procurement), and greater interest in system reliability, availability, and maintainability (McQueary et al. 2009). One particular approach that has been favoured among the test community is design of experiments (Seglie 2010) which has a long tradition in product development (Coleman and Montgomery 1993; Montgomery 2004) and dates back to the eighteenth century.

> Design of experiments (DOE) is rooted in the ability to provide a cost-effective way to perform more rigorous test planning.

The design of experiments (DOE) methodology is rooted in providing a cost-effective way to perform more rigorous test planning. Its main benefit is identifying the real operational envelope of a system and identifying an efficient test design that covers that envelope. This is accomplished by using modern statistical software to predict the performance of a system based on its design factors and their interactions. The additional rigour provided by DOE results in higher confidence (low probability of accepting a flawed system), higher statistical power (low probability of rejecting a sound system), and breadth (knowledge across the operational spectrum).

Applying DOE to developmental testing – where testers can perform controlled experiments – is adequate. However, operational testing – where emergent behaviours are more likely to occur – DOE has significant limitations. These include the following:

1. The assumption that the entire trade space is known
2. The ability to automatically replan the test strategy as emergent behaviours appear
3. The assumption that the value of each test and the feature it is designed to test are constant
4. The assumption that the cost of each test is the same

Cohen, Rolph, and Steffey (1998, p. 3) state: "…effective use of statistical methods is not limited to a determination of the appropriate sample size so that a test yields interval estimates at the required level of statistical confidence. It would often be preferable, given a fixed test budget, to design a test aimed at maximising the amount of information from the resulting test data in order to reach supportable statements about system performance".

We propose an approach that addresses the limitations of DOE and provides an answer to the need to maximise information for the least amount of cost. To illustrate such an approach, we describe how it could apply to the case of an unmanned and autonomous system.

The Curse of Dimensionality

The benefits of engineering systems, in particular when tight coupling exists, introduce tremendous challenges for testing (Newman 2001). For instance, Metcalfe's law (Gilder 1993) states that the value of a telecommunications network is proportional to the square of the number of connected users of the system (n^2). Following the same logic, more extensive networks are more expensive to test since the number of connections grows exponentially. This is known as the "curse of dimensionality" which describes the problem caused by the exponential increase in volume associated with adding extra dimensions to a mathematical space.

> The "curse of dimensionality" is the exponential increase in volume associated with adding extra dimensions to a mathematical space.

Solving multidimensional problems requires statistical techniques like Markov chains, Monte Carlo analysis, machine learning, Bayesian statistics, orthogonal arrays, and optimisation (Powell 2010). Researchers have explored the need for more testing of IT systems (Graves 2010) and advocated operational realism in testing (Stephens et al. 2008). However, neither Graves nor Stephens provides quantifiable recommendations for reducing the cost or schedule of testing. More recent work by Gibson (2012) showed that virtual machines can reduce testing time of engineering change orders by 11% by reducing setup and configuration time of Windows and Linux machines. While useful, the Gibson study did not explicitly address the curse of dimensionality problem associated with testing engineering systems.

The most rigorous study to date focused on reducing the cost of testing was done by Pfeiffer et al. (2011). Their results showed that test coverage of software systems is dramatically affected by test section strategy. However, the objectives of the Pfeiffer et al. study fall short in the following ways:

1. Their approach does not account for uncertainty in the information obtained by each test. What is missing is the estimate of a standard deviation to the value obtained from each test: the results of such tests are unknown during the planning process.
2. Similar to design of experiments, their approach assumes that the entire trade space is known in advance. What is missing is an approach that recognises that emergent behaviours will influence how the test strategy needs to evolve over time.
3. Similar to design of experiments, their approach assumes the cost of each test is the same. What is missing is an approach that uses a cost model to identify the approximate cost of each test independent of its perceived value.

With their increasing complexity, engineering systems fall into the class of systems where the science of testing can provide a step function improvement in the way they are tested. Accordingly, we propose an approach that addresses the limitations of DOE and the Pfeiffer et al. (2011) approach with the eventual goal of maximising information and minimising cost.

Developments in Testing

Extended life and increasing complexity dictates that testing methods and tools keep up with technological (different maturity levels), social/regulatory, and environmental requirements imposed on systems and systems of systems (SoS). These planned and potentially unplanned/undesired complications need to be considered when planning and performing testing. In respect to testing complex systems, approaches can address component-based technologies, design patterns, and resource allocation techniques. As discussed in this section, solutions to improve how tests are performed and planned through the utilisation of decision support systems (DSS), which support organisational decision-making are presented along with corresponding practical applications.

Application Example of Testing Methodology to an Unmanned and Autonomous System

As an example of an engineering system, an unmanned and autonomous system (UAS) like the DHL "Paketcopter" or Amazon's Prime Air delivery drone (Fig. 6), which provides package delivery, offers a unique opportunity for gradual technology insertion of automation due to task repetitiveness, relatively moderate sensory requirements, and the limited human exposure to safety risks. A key challenge is that the functional and non-functional elements of the system require extensive testing before they are deployed safely and effectively in operational environments. This challenge can be addressed through systematic test planning of heterogeneous, multi-agent autonomous systems. However, such a task is nontrivial because of the unstructured and dynamic environment of UAS operations. To address this challenge, an example for a test planning tool could incorporate a supervisory controller of the distributed agent-based platforms, a mission planner for human-robot tasking, and a decision support system (DSS) for extensive test planning validation.

This section shows an example of an innovative approach for testing engineering systems with emergent behaviour through the use of a decision support system and associated local linear or backstepping control algorithms (Madani and Benallegue 2008). The objective is to test the UAS control algorithms iteratively by exposing inner workings of heterogeneous agents, their interactions with the supervisory control system, and finally, the highest level of decision-making, mission planning

Fig. 6 Delivery drone (Mollyrose89 – Own work, CC BY-SA 4.0)

system. To accomplish this, it is possible to integrate a parametric cost model, knowledge gradient algorithm, and Bayesian updating algorithm embedded in a DSS.

The integration of automated technology in UAS faces significant challenges. UAS operations can be highly unstructured, dynamically changing, and heterogeneous. The execution of basic tasks requires the use of multiple pieces of equipment in a coordinated manner. An additional difficulty emerges from the use of different UAS platforms developed by a diverse number of companies. These UAS operation features suggest the need for automation to enable the capability to work cooperatively and self-adapt to dynamic changes.

Novel ideas to systematically handle the challenges in the automation of UAS emerge from the fields of robotics and automation, mainly due to recent efforts on multi-agent robotics and control. Multi-agent systems consist of interconnected dynamical systems capturing the behaviour of the individual entities intertwined within each other. In multiple UAS operations, each UAS may be defined by an agent, whereas cooperative algorithms within a communication infrastructure may define the interactions within the multi-agent, networked, and heterogeneous system.

It is necessary to collect data and information from all agents, the supervisory system, and the mission planning system to address this need. Using such data, measure of effectiveness can be used to determine the maturity of the UAS and its control algorithms. By integrating DSS to the UAS control system, we can identify an efficient test strategy of a complex heterogeneous UAS. The benefits include the following:

1. Reduction in testing time, effort, and cost
2. Reduction in uncertainty, unpredictability, and risk in testing
3. Rapid identification of new UAS capabilities

Decision Support Systems for Test Planning

The validation of local control algorithms is at the heart of autonomous functionality and can be accelerated with the help of a dedicated DSS that provides optimal test strategies to be executed (Ferreira et al. 2010). This iterative planning-replanning cycle can help ensure that the most critical scenarios are tested first so that the limits of the various control algorithms can be determined in the shortest amount of time. The importance of tests can be determined based on multiple criteria such as criticality to the user, human-robot interaction, cost, complexity, risk to human life, etc. These criteria can be selected with the help of parametric cost models, knowledge gradient algorithms, and Bayesian updating algorithms, which are described below (Valerdi and Blackburn 2009). Furthermore, the DSS can incorporate the human-in-the-loop by considering the collaborative role of humans and robots performing various tasks. The architecture of one such DSS, called the UAS Test Guru (Valerdi 2017), includes a human decision support system interface,

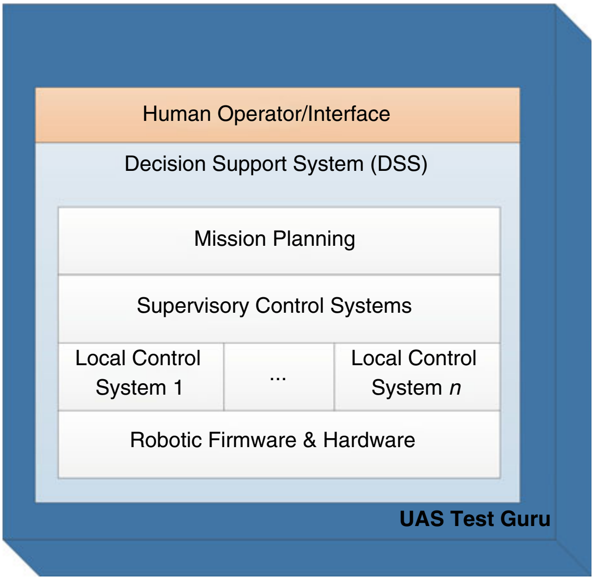

Fig. 7 UAS Test Guru hierarchy (Valerdi 2017)

high-level motion planner, and supervisory controller which allows for multiple criteria to be evaluated, as shown in Fig. 7.

The objective of the decision support system is to help identify the most critical tests that should be executed to obtain the highest amount of information in the shortest amount of time. This will help transition the test planning activity from a subjective and manual process into a more objective and automated process. We can accomplish this by applying approximate dynamic programming (Bertsekas and Tsitsiklis 1989; Powell 2011) and multi-criteria decision analysis (Keeney and Raiffa 1976; Howard and Matheson 1983) techniques.

Test Optimisation Using Decision Support Systems

Test planning can be extended to include automatic, adaptive, and multi-criteria balancing to enhance the robustness of the method being applied (Valerdi and Enhelder 2016). First, the DSS will accelerate test planning by automating (or partially automating) tasks that are currently human-intensive and error-prone (Valerdi 2017). The DSS will provide automated support for test planning tasks such as test prioritisation, test resource scheduling, and test strategy adaptation, among others (Valerdi 2017). The main goal is to offer a higher priority to test cases that have better-quality attributes for execution. For example, the DSS will perform test prioritisation by determining the relative value of candidate tests, considering both (1) the predicted importance and utility of the data yielded by each candidate test and (2) the cost of each candidate test, in terms of cost and schedule. Similarly, the DSS will assist test strategy adaptation by proposing ways to improve a set of test plans as more information about a system becomes known. For example, as the undesirable emergent behaviour of an unmanned and autonomous system is uncovered, test plans may need to be modified in order to mitigate the potential risks associated with these undesirable emergent properties.

Second, the DSS can utilise an adaptive planning component algorithm to search for the optimal path of knowledge acquisition (i.e. test sequence) (Valerdi 2017). The algorithm is inspired by traveling salesman and multi-armed bandit problems in operations research (Dayanik et al. 2008; Powell 2011), in which the player (in this case, the tester) has limited knowledge of the system and strives to maximise knowledge acquisition through the optimal sequencing of tests. This approach to testing is fundamentally adaptive in that it aids in constant replanning based on new information obtained from test results. Adaptive algorithms, also known as genetic algorithms, have been applied to a range of system optimisation problems but have not applied to test planning (Hess and Valerdi 2010).

The DSS can optimise test planning by addressing and balancing multiple criteria within a framework based on predetermined preferences. Specifically, the DSS applies formal decision-making techniques such as multi-attribute utility theory (Keeney and Raiffa 1976) to balance various stakeholder preferences. The use of quantitative methods allows the test process to deal more effectively than a human with the inherent complexity of co-robot environments where the many variables and unknowns do not allow “eyeballing” solutions to test planning challenges. In this way, the DSS facilitates the transition from function-based testing of single systems to mission-based testing of co-robot systems. Moreover, by assisting test planners in balancing trade-offs among cost, risk, and schedule when making test planning decisions, the DSS serves a particularly important role in the context of a rapid deployment of systems. The reasoning engine contains the co-robot system specific decision rules that can be adjusted based on user preferences. The outputs of the DSS will be fed to the control supervisor so that replanning tasks can be performed.

The DSS enables test planners to develop and refine a test strategy for co-robot systems that operate in any environment. The test strategies recommended by the DSS address multiple aspects of an overall test plan, including (Valerdi 2017):

- The level of human-robot interaction and the complexity of such tests
- The schedule and order in which to conduct different test events and activities
- The relative importance of various candidate tests, since some tests may need to be omitted due to cost, schedule, or other resource constraints
- The level of effort expected to complete a test plan and its constituent activities
- The resources needed to complete a test plan and the allocation of resources to test events and activities
- The risks associated with a test plan, such as a “domino effect” occurring if a test event fails or a test activity is not completed by a deadline
- The identification of potential undesirable emergent properties

- The options for altering or adapting the test plan as more information (cost, risks, schedule, etc.) is obtained or constraints or goals are changed

Thus, by using the DSS, test planners can create either the template for an initial test plan or refine and improve an existing test plan by incorporating the elements of the test strategy outlined by their stakeholders. For example, test planners might decide to move certain test events earlier in the schedule, eschew some test events due to unacceptable risks, request additional resources needed to gather important data, or reconfigure the test architecture to improve performance (Valerdi 2017).

The test planner's primary interaction with the DSS will be through a dashboard that will provide a user interface through which test planners specify the location of external data artefacts to use as inputs, invoke analysis components, and view test strategy reports containing the outputs of analysis, such as identified risks, recommended test sequences, etc. The dashboard will show what analyses are ready to execute, based on the inputs provided so far, what analyses have already been run, and the effects of any changes to the system configuration can influence test execution. The dashboard can simplify and streamline the human-robot interface of the test bed by enabling more efficient and effective use of resources to support planning-level decisions (Valerdi 2017).

Test Planning Algorithms

Test plans are dynamic entities and allow for the organisation of tests into logical groupings, to minimise redundancy and maximise test efficiency. Through the application of planning algorithms, it is possible to better arrange and schedule relevant system tests by evaluating fault detection as early as possible with minimalised cost and the associated time required for implementation (Oliver et al. 1997). By combining the proposed approaches for local/supervisory control design with a DSS, the validation of such algorithms can be performed much more efficiently and effectively. Smarter, more effective, and more efficient testing of systems can be realised with the help of a test planning tool to facilitate the prioritisation and sequencing of individual tests and composite test sets. These objectives can be accomplished by integrating parametric cost models, knowledge gradient algorithms, and Bayesian updating algorithms (Valerdi and Enhelder 2016).

To date, several adaptive algorithms for manual and automatic/semi-automatic planning have been developed (Hess and Valerdi 2010). However, many fall short in considering the organisational elements and have little respect for the collaborative role of humans and robots performing various tasks. The basis for a test planning algorithm can be described through the following steps (Valerdi and Enhelder 2016):

- Step 1: Prioritise system and/or mission requirements for the system under test. This will be accomplished using a systems-specific implementation of the Stakeholder Win-Win methodology, a multi-criteria preference analysis approach for requirements negotiation.

- Step 2: Define and quantify the cost, c, of running each test. This will be calculated using a *parametric cost model* that considers the complexities of the system under test and the resources (in terms of people, equipment, and facilities) needed to execute each test.

A parametric cost model is a group of cost estimating relationships used together to estimate entire cost proposals or significant portions thereof (ISPA 2008). These models include many interrelated cost estimation relationships, both cost-to-cost and cost-to-non-cost. While cost models have not explicitly been applied to testing in the past, they have been an essential part of product development for a long time. Our own analysis of UAS test events indicates that the most influential cost drivers are *number of systems to be integrated, integration complexity,* and *complexity of tests* as shown in Fig. 8. These technical costs driver scores demonstrate that tests are prioritised according to how complex the system or task is (Deonandan et al. 2010).

- Step 3: Determine $\overline{\theta}_d^o$, the initial estimate of the expected reward for making decision d, where each decision involves selecting a specific test that should be executed. In this case, a reward can be considered to be the generation of new knowledge about the system under test.
- Step 4: Determine $\overline{\sigma}_d^o$, the initial estimate for the standard deviation of $\overline{\theta}_d^o$. The standard deviation is based on the fact that the expected rewards are normally distributed. Higher values of $\overline{\sigma}_d^o$ indicate lower confidence in the decision under consideration.
- Step 5: Execute *knowledge gradient algorithm* to calculate the knowledge gradient (KG) index for feasible decisions. Since the KG jointly optimises three criteria, value, cost, and knowledge acquired, it can be used to develop a prioritisation of the system tests to be performed. At this stage in the process, the first phase of testing is performed and data is collected about the performance of the systems.
- Step 6: Execute *Bayesian updating algorithm* to re-calculate KG index based on new information (e.g. test results, shifting evolving mission requirements, test costs, test facility availability, etc.) and provide an updated test strategy based on the recommended prioritisation of a DSS similar to the UAS Test Guru.

Table 3 illustrates a set of simulated results for an example with five test options (Valerdi 2017). In this case, $\overline{\theta}$ represents the current estimate of the value of deciding to execute each test, while $\overline{\sigma}$ is the current standard deviation of each $\overline{\theta}$. Tests 1, 2, and 3 have the same value for $\overline{\sigma}$, but with increasing values of $\overline{\theta}$. The table illustrates that when variance is the same, the knowledge gradient prefers the decisions that appear to be the most valuable (high $\overline{\theta}$), as indicated by higher KG index score for Test 3. Tests 3 and 4 have the same value for $\overline{\theta}$, but decreasing values for $\overline{\sigma}$, illustrating that the knowledge gradient prefers decisions with the highest variance, as indicated by higher KG index score for Test 3. Finally, Test 5 appears to be the most valuable of all the decisions (high $\overline{\theta}$) but has the lowest variance meaning that

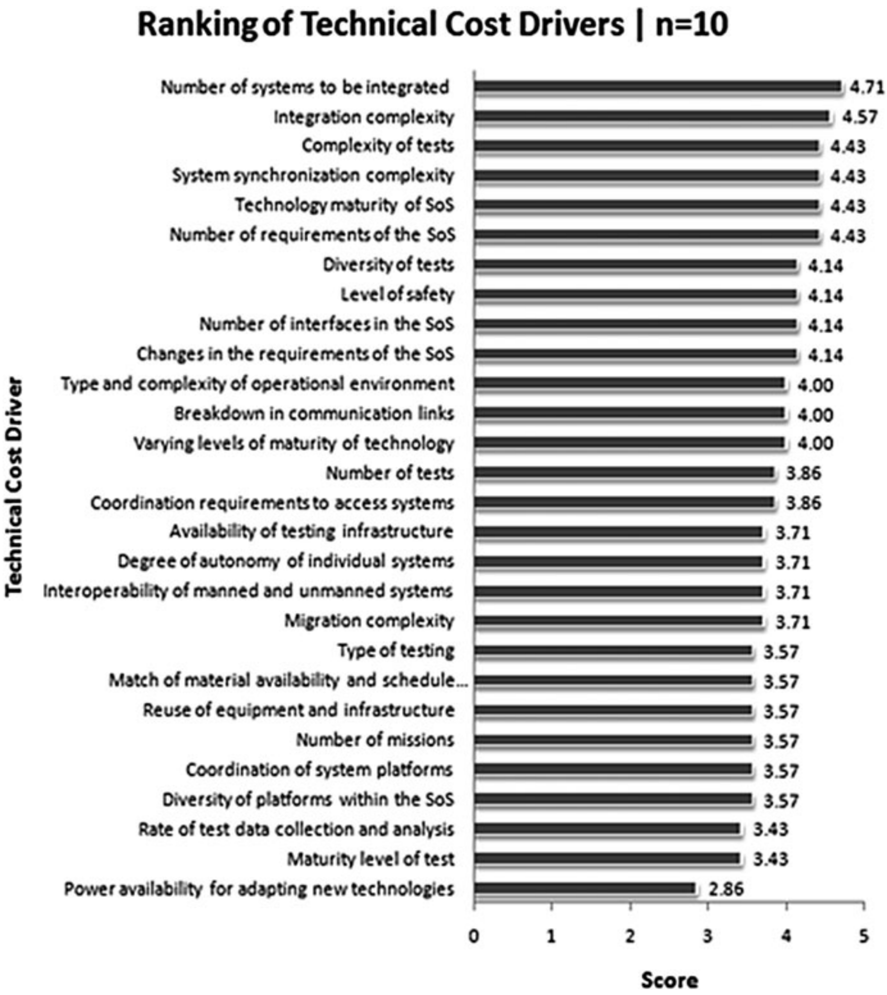

Fig. 8 Relative impact of technical cost drivers for UAS testing. (Deonandan et al. 2010)

Table 3 Knowledge gradient example

Test	$\overline{\theta}$	$\overline{\sigma}$	KG index
1	1.0	1.336	0.789
2	1.5	1.336	1.754
3	2.0	1.336	3.516
4	2.0	1.155	2.467
5	3.0	0.707	0.503

we have the highest confidence in this decision. Therefore, the best decision is to pursue Test 3 since it has the highest KG index score (despite the fact that it is not the most valuable in terms of $\overline{\theta}$).

The systems control algorithms (i.e. control and supervisory) and test planning algorithms when discussed (i.e. cost, knowledge gradient, and Bayesian) together form what is referred to as a human-in-the-loop DSS (reference UAS Test Guru). For the test planner to make the best decision possible, the user interface serves as a DSS, providing the highest amount of information in the shortest amount of time. The DSS as a collection point provides various resources needed to make test planning decisions such as the system(s) under test, cost/risk trade-offs, test progress, and test coupling.

Conclusion

As the demand and development of increasingly complex systems and SoS's continues, testing approaches and DSS will continue to change to improve human experiences and provide ultimately better systems (V&V). In reflecting on the chapter, by better understanding organisational aspects for conducting tests, the phase the test is being performed, the purpose for the test occurring, and the complexity of the system or SoS being tested, a more comprehensive and applicable strategy can be developed. This will help transition test planning activities from a subjective and manual process into a more objective and automated process.

In moving to application and concluding this chapter, the efficacy of the test planning algorithms described, or any of the test planning approaches for that matter, must be evaluated by the following criteria:

- Reduction in test planning time compared to existing manual approaches
- Speed at which test replanning can be done
- Reduction in test schedule through optimised plan provided by the algorithm
- Improved test coverage over time

While, not all of the criteria are equally important or even necessary for all circumstances, the organisational and complexity aspects previously discussed will support more efficient and effective testing. Applications of similar test optimisation methods applied to software testing have shown a 40% reduction in test effort in the financial services industry (Phadke and Phadke 2011) and a 90% reduction in test effort in the telecommunications industry (Cohen et al. 1997) representing millions of dollars of savings. We anticipate equivalent savings in testing engineering systems given similar technical characteristics and complexity.

Cross-References

► Designing for Emergent Safety in Engineering Systems
► Dynamics and Emergence: Case Examples from Literature
► Engineering Systems Design Goals and Stakeholder Needs
► Evaluating Engineering Systems Interventions

► Formulating Engineering Systems Requirements
► Properties of Engineering Systems
► Technical and Social Complexity
► Transitioning to Sustainable Engineering Systems

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Evaluating Engineering Systems Interventions

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Wester C. H. Schoonenberg and Amro M. Farid

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W. C. H. Schoonenberg (✉)
Laboratory for Intelligent Integrated Networks of Engineering Systems, Thayer School of Engineering, Dartmouth College, Hanover, NH, USA
e-mail: Wester.C.H.Schoonenberg.TH@Dartmouth.edu

A. M. Farid
Laboratory for Intelligent Integrated Networks of Engineering Systems, Thayer School of Engineering, Dartmouth Department of Computer Science, Dartmouth College, Hanover, NH, USA
e-mail: amfarid@dartmouth.edu; amro.m.farid@dartmouth.edu

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Abstract

Our modern life has grown to depend on many and nearly ubiquitous large complex engineering systems. Transportation, water distribution, electric power, natural gas, healthcare, manufacturing, and food supply are but a few. These engineering systems are characterized by an intricate web of interactions within themselves but also between each other. Furthermore, they have a long-standing nature that means that any change requires an intervention into a legacy system rather than a new "blank-slate" system design. The interventions themselves are often costly with implications lasting many decades into the future. Consequently, when it comes to engineering system interventions, there is a real need to "get it right." This chapter discusses two types of engineering system interventions, namely, those that change system behavior and those that change system structure. It then discusses the types of measurement that can be applied to evaluating such interventions. More specifically, it contrasts experimental, data-driven, and model-based approaches. It recognizes that only the last of these is appropriate for interventions that change system structure. Consequently, the chapter concludes with a taxonomy of engineering system models including graphical models, quantitative structural models, and quantitative behavioral models. The chapter concludes with a discussion of promising avenues for future research in the area, namely, hetero-functional graph theory and hybrid dynamic systems.

Keywords

Engineering systems · Evaluation · Interventions · Life cycle properties · Measures

Introduction

This chapter provides an overview of the background, context, and theory for evaluating engineering system interventions. So far, the Engineering System Design Handbook has provided (1) background and motivation for the engineering systems approach, (2) theory for describing engineering systems, and (3) an overview of intervention design for engineering systems. This chapter concludes the third part of the handbook with the background and framework to support the evaluation of engineering system interventions. The first section defines a point of departure for this chapter to enable the study of the chapter as an independent work. The section also refers to other chapters in the book to provide context and other relevant material.

The Emergence of Engineering Systems

In the context of twenty-first century grand challenges, the field of engineering systems has emerged at the intersection of engineering, management, and the social sciences. Over the past decades, engineering solutions have evolved from engineering artifacts that have a single function, to systems of artifacts that optimize the delivery of a specific service, and then to engineering systems that deliver services within a societal and economic context. In order to understand engineering systems, a holistic approach is required that assesses their impact beyond technical performance. Engineering systems are defined as follows:

Definition 1 Engineering system (De Weck et al. 2011) A class of systems characterized by a high degree of technical complexity, social intricacy, and elaborate processes, aimed at fulfilling important functions in society.

Furthermore, there are a number of characteristics that distinguish engineering systems from other systems. Engineering systems. . .

- . . . exist in the real world. They always have physical components, but are also likely to contain informational components.
- . . . are artificial. Engineering systems are man-made, but often integrate into the natural world.
- . . . have dynamic properties. Engineering systems change over time, and have a sense of temporality.
- . . . have a hybrid state. The states of engineering systems are usually both discrete and continuous.
- . . . contain some human control.

Some types of systems with these characteristics include electric power grids, transportation systems, healthcare delivery systems, the energy-water nexus, etc. This list is far from exhaustive, and the reader will find numerous other examples throughout the handbook.

The growth of engineering systems has been mostly organic and incremental. Many of these systems have been expanded or shrunk to match the changing (or perceived) needs over time. This has caused inefficiencies and unforeseen dynamics within those systems. The successful implementation of engineering system interventions relies on rigorous evaluation for a future-proof design.

The Importance of Evaluating Engineering System Interventions

As the complexity of engineering systems has evolved, there is need for a deeper understanding of the design and operation of engineering systems. Interventions were often designed and implemented with merely a theoretical understanding of their impact. During the rise of the automobile, many transportation infrastructure systems were overhauled to facilitate this new mode of transport (Jacobs 1961). However, the impact and outcomes of such changes were often unforeseen by policy makers. Today, we have the ability to much more accurately evaluate and understand the impact of interventions in engineering systems. Increased data and computational resources enable evaluation of interventions both *after* and *before* implementation (Lempert 2002).

The evaluation of interventions after implementation was especially useful when the computational resources to predict the outcomes of interventions were limited. The results of previous interventions guided new interventions and were eventually generalized as "rules of thumb." Furthermore, this type of evaluation also helped "tune" (or salvage) the intervention to get the best results. The downside of this trial-and-error approach is obvious; sometimes the interventions do not perform as intended. The failure to perform may become immediately obvious but can also materialize when the system has to function under extreme circumstances (Yeo 1995). An example of the latter scenario is the failure of the electric rail system in New York City during hurricane Sandy. The rain ahead of the hurricane flooded several transformers, and the power supply for the rail system was interrupted. As a result, the rail system failed, and evacuation of lower Manhattan was severely interrupted. It took a major hurricane to demonstrate the limitations of the electrification of the rail system, whereas it had been operated successfully for decades before.

In order to improve interventions before they are implemented, evaluations are now often performed *before* they are implemented. The goal is to determine if the intervention will improve the system outcomes before a large investment is made and society has been interrupted (Muhanji et al. 2019). Furthermore, predictive evaluations can be used to evaluate if the improvement is large enough to outweigh the downsides of the intervention. One of the challenges is to accurately represent the real-world system with computer models. When the system has not been represented accurately, an intervention can work well in the simulations but may underperform in reality. In theory, the more extensive the model, the more accurate the prediction, but in reality this is often not feasible due to the financial constraints to build a complex model and the computational constraints to simulate it. Therefore, a balance between simplifying and detailed modeling is required.

When it comes to engineering system interventions, there is a real need to get it right. Engineering systems are inherently socio-technical, they impact and are impacted by people. Furthermore, they are expensive to build and change. This chapter discusses both the predictive and the post-implementation evaluation of engineering system intervention.

Chapter Outline

- **What Is an Intervention?** In order to evaluate engineering system interventions, first the word "intervention" must be understood. Engineering systems are most often legacy systems, and any change to the system is inherently an intervention of some type. Section "What Is an Intervention?" discusses systems and the different types of interventions.
- **Evaluation Requirements**. Artifacts, systems, and other things can be measured in one of two ways: (1) direct measurement and (2) indirect measurement. These

two types of measurement bring along their own set of specific requirements in order to result into a holistic and appropriate evaluation of the engineering system intervention. Section "Requirements for Evaluating Interventions" discusses the fundamentals of measurement and their application to engineering systems.

- **Comparing Evaluation Methods**. Evaluation of engineering system interventions requires a deep understanding of the impact of the intervention on the outputs of the system. Section "Comparing Evaluation Methods" provides an overview of three approaches to intervention evaluation methods.
- **Model-Based Intervention Evaluation**. Finally, the chapter concludes with a discussion around the importance of data and systems theory in the evaluation of engineering systems. Model-based evaluation approaches leverage theory to enable intervention evaluation for engineering systems. Section "Model-Based Intervention Evaluation" provides an overview of some of the most important system modeling methods.

What Is an Intervention?

This section introduces a holistic understanding of the meaning of *interventions*. This is realized by first summarizing the description of a system to define a consistent framework. Based on this framework, for the purposes of this chapter, a definition of *interventions* and a discussion around the types of interventions are provided. The type of intervention is critical when making a decision about the type of evaluation method, as discussed in section "Comparing Evaluation Methods."

Describing Systems

Engineering systems, also referred to as socio-technical systems, are complex systems at the intersection of physics, management, and social sciences (De Weck et al. 2011). The evaluation of engineering system interventions relies on accurate and consistent measurement of the system. As shown in Fig. 1, this chapter adopts the approach of many STEM disciplines where systems are mathematically described as a system of differential algebraic equations (DAEs) that define the relationship between the inputs u and the outputs z (Edwards et al. 2018; Kulakowski et al. 2007). The system is also said to have states x, algebraic states y, and parameters λ. The vector functions $f(\cdot)$, $g(\cdot)$, and $h(\cdot)$ are differential equations, algebraic equations, and output equations, respectively. While a more complex model based upon the hybrid dynamic system literature is possible, a system of differential algebraic equations serves the purposes of this discussion.

In addition to the above description, this chapter requires the introduction of four systems thinking abstractions: (1) system context, (2) system function, (3) system form, and (4) system concept (De Weck et al. 2011; Farid 2016). These abstractions support the classification of intervention types and their accompanying evaluation methods.

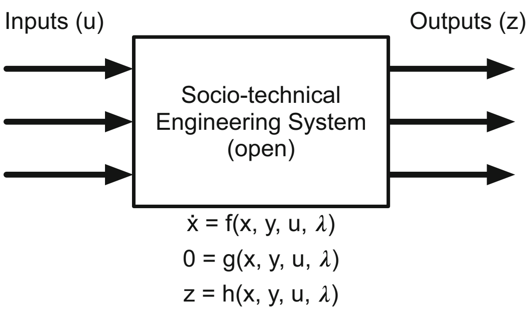

Fig. 1 A mathematical and graphical representation of an arbitrary engineering system

System Context

The system context is the set of interrelated conditions in which the system exists or occurs (M.-W. Dictionary 2019). Sometimes, it is also referred to as the system environment: *"all that is external to the system"* (Rowell and Wormley 1997). The field of engineering systems emphasizes that the system does not operate in a vacuum but rather is solidly placed in its context. When an intervention is evaluated, the impact of the system on the context is critical to truly understand the system's performance. Sometimes, these outputs are neglected with severe consequences (e.g., climate change). Naturally, the context also influences the system itself, and often, it determines the success of the intervention.

System Behavior

System behavior is the response of system outputs to a change in system inputs or parameters. It reflects the processes or function of the system: "what the system does." The system inputs are predominantly a result of the system context, whereas the parameters are internal to the system. In the context of *engineering systems*, the system behavior consists of the behavior of the engineering artifacts and the humans that interact with the system.

System Form

System form is the description of a system's component elements and their relationships. The system structure also defines the presence (but not values) of system states x, algebraic states y, parameters λ, inputs u, and outputs z. By adding or removing elements to/from the system, the number of equations in the vector functions $f(\cdot)$, $g(\cdot)$, and $h(\cdot)$ changes.

System Concept

The description of the system as a whole relies on the combination of the system behavior and the system structure. System concept is the mapping of system function onto system form (also called the allocated architecture Buede 2009). Consequently, a system of equations can represent system concept. The behavior of the system results from the coupled equations.

Describing Interventions

For the purposes of this chapter, *"intervention"* is defined as follows:

Definition 2 Intervention: (M.-W. Dictionary 2019) The act of interfering with the outcome or course especially of a condition or process (as to prevent harm or improve functioning).

In the context of engineering systems, interventions intend to change the system so as to improve the outcome of the engineering system. Two types of interventions are recognized: behavioral and structural.

Behavioral Interventions

Behavioral interventions aim to change the outcomes of a system by adjusting the values of the system inputs and system parameters while the structure of the system is untouched. As a result, behavioral interventions are often relatively affordable. Decisions to change the operating procedure or policies around a system may take a long time and are sometimes hard to implement, but the upfront capital investment is limited because no fundamental changes in the system are necessary.

An example of an intervention based on system inputs is a policy change that increases the ethanol percentage in gasoline. When a different ethanol/gasoline mixture enters the system, the emissions of the transportation system will change as a consequence.

An example of an intervention based on system parameters is the reduction of ticket prices in a public transit system. Ticket prices are internal to the engineering system and are set as a result of a policy decision. As a consequence of this parameter change, the total public transit ridership may increase/decrease, with cascading impacts such as less/more traffic, less/more emissions, etc.

Structural Interventions

Structural interventions aim to change the structure of the system: its parts and the relationships between them. These changes are often physical and require large upfront capital investments. Furthermore, structural interventions require a revision of the operating procedures and policy around the system, since the policies of the old system may no longer apply.

An example of adding elements to the system is the addition of a road in a town. This road adds an "equation" and a "state." For example, a description of the traffic flow on the road is a result of the number of vehicles on the road. Such a structural intervention leads to a revision of the local traffic ordinances. For example, at the connecting intersections, a new speed limit may be introduced to reduce the risk for turning vehicles.

An example of adding variables is the consideration of electric vehicles for parking lot design. Electric vehicles require charging facilities on the parking lot, which changes the calculation of the required parking spots in building code.

This section first introduced a common framework for describing systems using four systems thinking abstractions. These distinct abstractions are the basis for the selection of the appropriate method for evaluation of the intervention (to be discussed in section "Comparing Evaluation Methods").

Requirements for Evaluating Interventions

This section discusses measurement as a foundation for the evaluation of engineering system interventions. Interventions aim to improve the existing engineering system. Consequently, the evaluation of interventions requires a comparison of (at least) the current system and the system with the intervention. Such a comparison requires the definition of a common mathematical framework (or standardizing space) to describe both systems. The process of first defining this framework and then describing the systems within the framework is called *"measuring."*

This section first discusses the fundamentals of measurement including an overview of the generic measurement process, measurement scales, and different measurement strategies. The second part of this section then discusses different approaches to measurement and, specifically, the differences between measuring a technical system and an engineering system. Based on this foundation in the measurement of engineering systems, section "Comparing Evaluation Methods" discusses the evaluation methods for engineering system interventions.

Measurement Fundamentals

The measurement of engineering systems is critical for informed decision-making. As shown in Fig. 2, without measurement, the real world presents us with an empirical system that exhibits certain phenomena called empirical results. These results can be viewed as qualitative or anecdotal evidence. Nevertheless, the link between the empirical system and its empirical results is often not well understood, and consequently the associated intelligence barrier prevents effective decision-making. Instead, the empirical system is first *measured* so that real-world phenomena are assigned their associated numerical values in a formal (mathematical) system. Mathematics and statistics, more specifically, are then used to determine

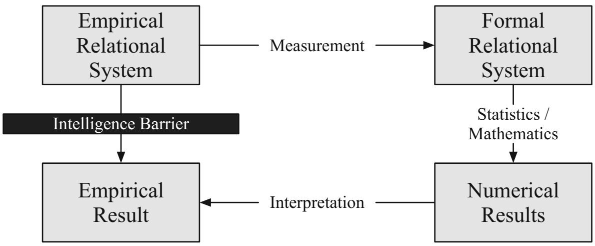

Fig. 2 A generic measurement process (Farid 2007)

numerical results in the formal system. These are, in turn, interpreted to become empirical results. Without an accurate and consistent approach to measuring the empirical system, the foundation for the decision-making process is flawed. Consequently, the empirical and formal systems must possess methods by which their respective objects can be *related* and ultimately compared.

More specifically, the e**mpirical relational system** contains a nonempty set of empirical objects that are to be measured, with relations between and closed binary operations on the empirical objects. Note that these relations are *independent* of the measure function. The f**ormal relational system** is a nonempty set of formal objects with relations between and closed binary operations on the formal objects.

Definition 3 Measurement (Finkelstein 1982, 2005): "Measurement is the process of empirical, objective assignment of symbols to attributes of objects and events of the real world, in such a way as to represent them, or to describe them." – Finkelstein, 1982

Measurement consists of three elements: (1) a set of measurables, (2) a standardizing space, and (3) a measure function. The set of measurables is defined as a set of objects with a specific attribute type. The standardizing space is a basic construct to which all the measurements can be compared. Finally, the measure function performs the empirical and objective assignment as mentioned in the definition of measurement. A consistent measure function ensures a consistent measurement of empirical relational systems to formal relational systems. If two empirical systems have been translated to formal systems with the same measure function, the formal systems can be compared rather than their respective empirical systems.

Definition 4 Measure (Farid 2007): A measure (or measure function) is a one-to-one function that acts on a set of (empirical) objects and returns a formal object.

Note that often the term "measure" and "metric" are confusing. Metric, however, is defined as follows:

Definition 5 Metric (Čech and Katětov 1969): A metric, also called a distance function, defines the distance between a pair of elements in a set.

Not all empirical relational system can be measured in the same way. For example, human behavior and a block of iron do not have the same attributes. The type of empirical system, with the related attributes, determines the type of measurement scales that can be used to measure the system. This impacts the type of numerical results downstream in the measurement process, because not all mathematics and statistics can be used for all measurement scales. The scale types, with applicable statistics and examples, are presented in Table 1. Engineering systems inherently combine physics-based systems with human behavior and economics. Consequently, the measurement of the engineering system requires a combination of the measurement scales.

Table 1 Classification of measurement scales (Farid 2007)

Scale type	Applicable statistics	Example
Nominal	Nonparametric	Football player uniform numbers
Ordinal	Rank order and above	IQ
Interval	Arithmetic mean and above	Celsius scale
Ratio	Percentage and above	Kelvin scale
Absolute	Additivity and above	Counting

From a practical perspective, there are two measurement strategies: (1) direct measurement and (2) indirect measurement. Direct measurement is applied when the desired property is both "simple" and an "output" of the system. As a result, the property is easily accessible, and there are often sensors that directly convert the desired property into a numerical result. Fundamental measures like length, time, voltage, and current are examples. However, these properties are rare, especially for engineering systems. Indirect measurement applies to properties that are not fundamental. These properties require the combination of fundamental properties that are considered "internal" to the system, into a formal model. The formal model is considered the standardizing space, and mathematics and statistics are applied to this model to extract the desired numerical results.

Engineering System Measurement

During the past century, engineering solutions have evolved from engineering artifacts to engineering systems. Consequently, the solution requirements have changed. Instead of merely "functioning" artifacts that performed their (singular) task, engineering systems perform many services composed of separate tasks. Furthermore, engineering systems include non-technical elements, more specifically humans. It is, therefore, essential to evaluate engineering systems beyond their technical aspects and include impacts of the system on its environment.

This section describes engineering system measurement with a tiered approach. Engineering systems are evaluated at several levels of granularity. First, the fundamental artifacts are evaluated based on the performance of their specific task with technical performance measures (TPMs). Then, the combination of these artifacts provides a service. The performance of these services is measured with measures of performance (MOPs). The first two types of measures, however, do not truly address the socio-technical nature of engineering systems. Therefore finally, measures of effectiveness (MOEs) were developed at the highest level of granularity for engineering systems. These consist of multiple services and socio-technical interfaces. For the engineering systems literature, a subset of these measures is especially important: *life cycle properties* or *ilities.*

Definition 6 Technical performance measures (SE Handbook Working Group 2015): "TPMs measure attributes of a system element to determine how well a system or system element is satisfying or expected to satisfy a technical requirement or goal."

Definition 7 Measure of performance (SE Handbook Working Group 2015): "The measures that characterize physical or functional attributes relating to the system operation, measured or estimated under specified testing and/or operational environment conditions."

Definition 8 Measure of effectiveness (SE Handbook Working Group 2015): "The operational measures of success that are closely related to the achievement of the mission or operational objective being evaluated, in the intended operational environment under a specified set of conditions; i.e., how well the solution achieves the intended purpose."

Overall operational success criteria (measures of effectiveness) include mission performance, safety, operability, operational availability, etc. These measures of effectiveness are often a quantitative means of measure a degree of adherence to requirements.

Finally, in the context of engineering systems, life cycle properties or *ilities* need to be addressed as a subset of the MOEs. The definition of ilities is:

Definition 9 "Ilities" (De Weck et al. 2011) "The ilities are desired properties of systems, such as flexibility or maintainability (usually but not always ending in 'ility'), that often manifest themselves after a system has been put to its initial use. These properties are not the primary functional requirements of a system's performance, but typically concern wider system impacts with respect to time and stakeholders than are embodied in those primary functional requirements. The ilities do not include factors that are always present, including size and weight (even if these are described using a word that ends in 'ility')."

The measurement of engineering system interventions often relies on a large number of measures that aim to capture the full impact of the intervention. It thus becomes challenging to weigh all the trade-offs appropriately when comparing intervention options. In these situations, the measures are often summarized or combined through weighted objective methods (WOM). A WOM aims to reduce the complexity by, first, assigning a value to the performance of the measures in the analysis and then manipulating (adding, averaging, etc.) these values to combine them into a single score for the intervention option. When executed thoughtfully, this approach can provide a valuable, high-level overview of the intervention options.

The downside of a WOM is that it relies on the *combination* of measurement functions for many different measures. These measurement functions generally do not have the same scale. Consequently, the combination of the results of the individual measures into a single measure is flawed.

More concretely, for each measure, the WOM may rank the intervention options from best to worst. For example, the most resilient intervention receives rank 1 on the measure "resiliency"; the least resilient intervention receives rank 5. When these ranks are combined in a WOM, for example, by averaging the rank of an intervention over all the measures, one violates the statistics of the rank scale. The “ordinal” scale, as mentioned in Table 1, does not allow for additive statistics. Therefore, the WOM that ranks the interventions on the measures and then takes the “average rank” uses flawed statistics.

This section described (1) how to measure and (2) what to measure. The former was described through the process of measurement, and the latter was described through three categories of engineering system measures in increasing scale. The chapter now builds on this knowledge to compare evaluation methods for engineering systems.

Comparing Evaluation Methods

This section discusses the different types of evaluation methods for engineering system interventions. As discussed in section “What Is an Intervention?,” Fig. 1, engineering systems create a relationship between inputs and outputs. The interventions aim to improve the outputs of the system, given a set of inputs. The goal of the evaluation methods is to predict how an intervention changes the outcome of the engineering system. Generally, the relationship between inputs and outputs of systems has been studied using one (or a combination) of three approaches.

The experimental approach was used at the origin of science. In this approach a hypothetical relationship is tested through a set of experiments in which either the inputs are changed or the system is changed (Felson and Pickett 2005). The experimental approach is generally performed in a controlled environment.

With the rise of widely available (historical) data on engineering systems, the data-based approach became viable. In this approach, instead of developing a controlled experiment with the system, existing data is used to derive a relationship between inputs and outputs of the system (Washington et al. 2003).

Finally, when all the parts of the engineering system are well understood, a theoretical model can be built to reflect the existing knowledge of the system (De Weck et al. 2011). This model-based approach combines all the parts of the system to explain the relationship between the inputs and outputs of the system. Interventions can be evaluated by testing the response of the model to changes in input data and the parts of the model.

These approaches are not mutually exclusive and are often combined to grasp the full complexity of engineering systems. Each of these evaluation methods has been adopted across fields, both in academia and industry. Note that all approaches can be used to study interventions both qualitatively and quantitatively. The measurement scale depends on the type of intervention and the desired analyses that support the interpretation of the results. This section continues to discuss each of the evaluation methods.

Experimental Approach

The experimental approach for the evaluation of engineering system interventions relies on the comparison of two sets of empirical results before and after the intervention. The main benefit of this approach is that the results are real. As long as the measurement process is kept constant for both measurements, the empirical results reflect a change in the objects of the empirical relational system (or real world) (Broto and Bulkeley 2013). Furthermore, the results from such an experimental approach hold for both behavioral and structural interventions. Note that experiments are also valuable to study specific pieces of engineering systems with small-scale experiments, often in a well-controlled environment.

The experimental approach, however, has numerous disadvantages. Engineering systems are generally large, critical systems intertwined with the daily routine of the population (Karvonen and Van Heur 2014). Experimenting with these systems to find out which approach works best, potentially rebuilding systems multiple times, is a tremendous waste of money (Felson and Pickett 2005). Furthermore, the execution of such an experiment is time-consuming and potentially reckless. The experimental approach should, therefore, only be used sparingly and mainly to inform the planning of future interventions (e.g., as in the case of pilot projects) (Caprotti and Cowley 2017). The value to provide "lessons learned" to future interventions should not be overestimated. Another downside of the experimental approach is that it is a black box model. The system as a whole is overhauled, but it may be unclear how external factors have changed between the time of the baseline measurement and the post-implementation measurement.

Data-Driven Approach

The data-driven approach to the evaluation of engineering system interventions relies on the definition of a statistics-based formal relational model between inputs and outputs. This model can be used to evaluate a behavioral intervention by estimating the response of the system to changing inputs. Generally, six types of data analysis are distinguished (Leek and Peng 2015):

Descriptive data analyses aim to describe the data without interpretation (Navidi 2008). The most commonly used statistics in quantitative descriptive analyses are the sample mean and the sample standard deviation. A summary statistic for nominal measurements is a frequency analysis.

Exploratory data analysis provides a description and interpretation of the data aimed at providing insight into a problem (Behrens 1997). The goal of exploratory data analysis is to find the "story" of the data, detect patterns and trends, and inform deeper study of the data. Some of the most common techniques include graphical representation of the data with boxplots, dotplots, or kernel density functions. Exploratory data analysis can also include preliminary model building and subset analyses.

Inferential data analysis aims to provide general facts about a certain type of systems given a limited amount of data (Lowry 2014). It quantifies the correlation between measurements to provide insight in the generalizability of the patterns in the data. The two major branches in inferential data analysis are estimation and hypothesis testing. The former contains the main methods of point estimation and interval estimation. The latter contains a wide range of tests appropriate for different types of analyses. A non-exhaustive list of hypothesis tests is provided below (Christensen et al. 2011): (1) t-test for independent means, (2) t-test for correlation coefficients, (3) one-way ANOVA, (4) analysis of covariance, (5) two-way ANOVA, (6) one-way ANOVA with repeated measures, (7) t-test for regression coefficients, and (8) chi-square for contingency tables.

Predictive data analysis measurements of a subset to predict the measurement on a single person or unit. The algorithms in this field are evolving quickly, and they are often classified into supervised learning and unsupervised learning. Supervised learning aims to learn a function that couples inputs to outputs from data that contains both inputs and outputs. A non-exhaustive list of supervised learning algorithms is as follows (Caruana and Niculescu-Mizil 2006): (1) support vector machines, (2) neural nets, (3) logistic regression, (4) naive Bayes, (5) memory-based learning, (6) random forests, (7) decision trees, (8) bagged trees, and (9) boosted stumps. Unsupervised learning is predictive data analysis without a pre-identified output or feedback. Some typical unsupervised learning examples are as follows (Sammut and Webb 2017): (1) clustering, (2) association rules, and (3) self-organizing maps.

The final two methods, c**ausal data analysis** and m**echanistic data analysis,** rely on a theoretical understanding of the measured system and are used in conjunction with model-based evaluation approaches. Causal data analysis derives an average effect of one measurement on another, whereas mechanistic data analysis aims to determine the relationship between two measurements under all conditions.

All analyses can be used to inform the design of the intervention. However, for the definition of the formal relational model that "predicts" the relationship between inputs and outputs after the intervention, only the last three types are appropriate. Note that the statistical model requires data beyond historical data of the original system (Washington et al. 2003), for example, from other systems comparable to the post-intervention system.

The benefits of the data-driven approach are that it is both cheap and quick. The cost of collecting and storing data has plummeted while the availability has soared. In combination with rapidly evolving computational resources that can analyze the data, the creation of a data-based model has become very affordable. Furthermore, the rise of cloud computing enables extremely fast analysis of the data.

The downsides of the data-driven approach are related to the fact that statistical models are a black box (Washington et al. 2003; Caminha et al. 2016). As a result, it is impossible to truly understand the elemental dynamics that define the overall system behavior. This is especially true for more advanced and automated statistical models based on neural networks and deep learning (Samek et al. 2017). As a result of the opaque nature of the model, the study of structural interventions is not possible. The model loses its generalizability when the basic equations (or assumptions) are changed. Finally, the data-driven models rely on the assumption that the system is stationary. In order to analyze interventions that break the "business-as-usual" case, data-based approaches to intervention evaluation are insufficient.

In conclusion, data-driven models are predominantly appropriate to analyze behavioral interventions in systems where the "mechanistic" science is not fundamentally understood. However, the analysis of structural interventions, or interventions that break the assumption of "business-as-usual" in any way, cannot be performed with data-driven evaluation approaches.

Model-Based Approach

The model-based approach to the evaluation of engineering system interventions relies on the construction of a formal relational system based on knowledge of the empirical system (Guizzardi 2007). The formal relational system is constructed to represent the dynamics of each of the elements in the empirical relational system. The combination of each of the elemental models creates full system results that match the observed numerical results as derived from the measurement of the real-world system. The intervention is evaluated by implementing new or changed elemental models in the formal relational system. The empirical results interpret the numerical results of the two formal relational systems. Section "Model-Based Intervention Evaluation" provides a closer look at the different model-based approaches to evaluating engineering system interventions.

The main benefit of the model-based approach is its transparency (Schoonenberg et al. 2018). The elements in the models are known and have individual properties. The properties may include first principle-based dynamics. Furthermore, the model-based approach supports the evaluation of both behavioral and structural interventions. The model elements may be adjusted in their behavior or be changed all together.

The main downside of the model-based approach is that a deep knowledge of the engineering system is required to build a model that matches the real-world measurements (Schoonenberg et al. 2018).

In conclusion, model-based intervention evaluation is specifically valuable when used to represent a system that is well known. It provides a transparent approach to the evaluation of both structural and behavioral interventions. In recent years, a discussion around the "end of theory" has emerged. The chapter addresses this discussion explicitly in the next section ("Model-Based Intervention Evaluation", together with an in-depth discussion of the model-based intervention evaluation methods. This section discussed three central approaches to the evaluation of engineering system interventions with their respective strengths and weaknesses. The next section provides extra detail on the last of these approaches.

Model-Based Intervention Evaluation

The previous section provided a comparison of the different methods for the evaluation of engineering system interventions. This section takes a closer look at the model-based intervention evaluation methods. Some literature has posited the "end of theory" given the explosion in the availability of data (Anderson 2008). This section, however, demonstrates that theory plays an essential role in the future of engineering systems (Smaldino 2019; Mazzocchi 2015; Succi and Coveney 2019). The discussion is structured in congruence with the classification of modeling methods as displayed in Fig. 3.

The development of theory is critical to the future of engineering system design and intervention evaluation because . . .

- . . . it defines meta-data features in data collection.
- . . . it ensures a deep understanding of the modeled system so that both structural and behavioral interventions are understood.
- . . . it ensures a deep understanding of the modeled system such that the knowledge gaps are explicit. It requires assumptions and has the ability to inform future research (to test those assumptions).

Model-based evaluation of interventions does not forego the use of data and experiments. Rather, they leverage those in testing assumptions and creating a deeper understanding by extensive simulation and testing.

Graphical Models

The first class is graphical models. These models have been used to describe a wide range of systems, from technical to socio-economic. Graphical models are qualitative in nature, and they are often used to communicate the structure of a system. Furthermore, they are also used to communicate qualitative information and the ontology of a system or a class of systems. Furthermore, graphical models are not limited in the heterogeneity of the modeled system.

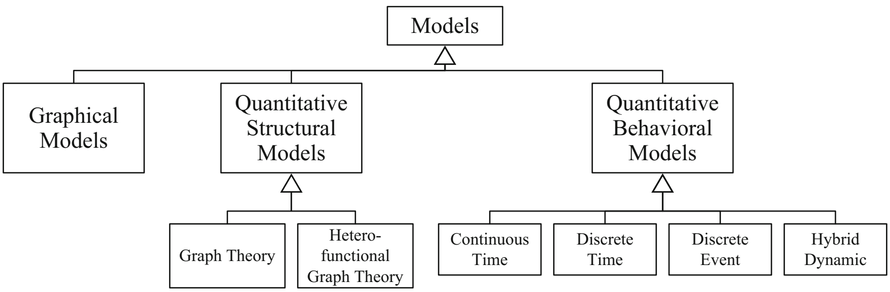

Fig. 3 Classification of modeling methods for the evaluation of engineering system interventions

The downside of graphical models is the lack of support for quantitative analyses of the models. However, some methods have been developed to gain quantitative insights based on graphical modeling methods. These are often developed as part of a specific software package for the modeling method.

Below, a number of graphical modeling methods are introduced as a rough overview of the landscape. This list is not exhaustive, but it provides the reader with a starting point.

IDEF0 diagrams enable the decomposition and architecture of system function (Anonymous 2001). For each function, IDEF0 lays out the inputs, controls, and mechanisms required to create the output. For clarity, the method relies on aggregation and decomposition of processes to limit the number of processes to six per layer of modeling abstraction. IDEF0 is one of the IDEF families of modeling languages. These languages have been developed starting in the 1970s with funding from the US Air Force.

Unified modeling language (UML) was developed to provide a consolidated approach to object-oriented modeling methods (Rumbaugh et al. 2005). UML was originally intended for software and firmware, but its strengths were recognized and the methods were applied to other fields.

Systems modeling language (SysML) borrows many features of UML and customizes them for cyber-physical systems. These include block definition diagrams and activity diagrams. SysML also includes a new set of diagrams to address the physical nature of these systems (e.g., the internal block definition diagram) and direct support for requirements engineering (SE Handbook Working Group 2015). SysML is the most commonly used modeling language among systems engineers.

Model-based systems engineering created the systems modeling language (SysML) as an abstracted graphical model with sufficient ontological breadth to integrate and synchronize more detailed domain-specific engineering models. SysML is not meant to develop complex mathematical models that provide engineering insight, as it is qualitative and graphical in nature. Rather, SysML provides systems engineers and project managers with a tool by which to quickly understand the overall structure and behavior of a system and its component modules so as to coordinate its engineering development in large and often multiple engineering organizations.

SysML leverages multiple modeling frameworks to represent the full breadth and complexity of an engineering system. This multitude of diagrams allows the modeler to separate, for example, form from function to study the processes in a solution-neutral environment. The downside of using SysML is that the modeler needs to leverage the right diagrams to model the system.

Object-process methodology (OPM) has been developed explicitly for the modeling of general purpose systems with both system form and behavior in mind (Dori 2002). OPM describes form and function in a single diagram, with a single, consistent hierarchy. OPM has the benefit of having a single hierarchical model and using a single type of diagram to represent the full system. However, OPM is missing the breadth to capture all aspects of a system.

Business process model and notation (BPMN) is developed to support decision-making around business processes (OMG 2011). The goal is to provide a language that can be intuitively understood by all stakeholders of the process. BPMN has overlap in functionality with activity diagrams in SysML, but BPMN is specifically designed for business processes, and activity diagrams have a much broader applicability.

Causal-loop diagrams have been used to describe socio-technical systems. These use a directed graph approach to connect (hard and soft) variables as feedback loops. Causal-loop diagrams are easy to understand by stakeholders and can enable conversations about the dynamics of a system. The downside is that causal-loop diagrams quickly become complex and that the method does not lend itself for a hierarchical decomposition of the system. "System *d*ynamics" is a quantification of causal-loop diagrams. It was first developed in the 1950s at MIT to model nonlinear behavior with stocks, flows, and feedback loops (Forrester 1994). Over time, it has evolved to address a variety of dynamically complex systems. System dynamics can be used both qualitatively, to describe and model systems, and quantitatively, to simulate dynamic behavior with the VenSim or Stella software packages.

Quantitative Structural Models

Quantitative structural models mathematically describe a systems structure.

Definition 10 System structure (Farid 2007; Schoonenberg et al. 2018) is defined by the parts of a system and the relationships among them. It is described in terms of (1) the system boundary, (2) the formal elements of the system, (3) the connections between them, (4) the functional elements of the system, and (5) their allocation to the formal elements.

Quantitative structural models have been used extensively to describe both social and technical systems. In all cases, they rely heavily on graph theoretical concepts.

Graph Theory

A **Network** (or graph $\mathcal{G}$) is a general means of representing patterns of connections or interactions between parts of a system (Newman 2009). The parts of the system are represented as nodes (or vertices $\mathcal{V}$). The connections or interactions are represented as lines (or edges $\mathcal{E}$). In addition to this set-theoretic definition, graph theory provides incidence and adjacency matrices as means of algebraic analysis. Networks are used to study systems in a wide variety of disciplines including the Internet, power grids, transportation networks, social networks, citation networks, biochemical networks, and neural networks among others. Objectively speaking, the definition of a graph $G = \{V,E\}$ captures only the first three (of five) parts of system structure. Consequently, one of the major shortcomings of graph theory is the failure to represent heterogeneity in networks as a result of the simplicity of its mathematical structure. Instead, many works attribute additional data *features* to graphs to expand their utility.

The d**esign structure matrix**, for example, is a type of network modeling tool (Eppinger and Browning 2012) that seeks to distinguish the different types of interconnections within a system. The four types of design structure matrix models are (1) product architecture, (2) organization architecture, (3) process architecture, and (4) multidomain architecture.

Multilayer networks expand on existing network theory to accommodate the study of networks with heterogeneity and multiple types of connections (Kivelä et al. 2014). Over the past decade, numerous methods have tried to provide a consistent approach to model these networks of networks. However, as discussed by Kivela et al., all these multilayer network methods have their respective modeling limitations.

Hetero-Functional Graph Theory

Hetero-functional graph theory has emerged over the past decade to be the first quantitative structural model that captures all five parts of system structure (Schoonenberg et al. 2018). It enables the structural modeling of a heterogeneous large flexible engineering system and explicitly accommodates all five types of system processes (i.e., transform, transport, store, exchange, and control) and all five types of operands (i.e., living organisms, matter, energy, information, and money) that regularly appear in engineering systems (De Weck et al. 2011). Furthermore, hetero-functional graph theory has been used as the underlying structure for dynamic system models across many different application domains including power, water, transportation, production, and healthcare systems. It has also been used to study the interdependencies of these systems within the context of interdependent smart city infrastructures.

Quantitative Behavioral Models

Quantitative behavior models can be broadly classified as (1) continuous time behavioral models, (2) discrete time behavioral models, (3) discrete event behavioral models, and (4) hybrid dynamic behavioral models.

Continuous Time Behavioral Models

Continuous time and discrete time behavioral models are closely related and can both be further classified into time-varying vs. time-invariant and linear vs. nonlinear models. For more details about that decomposition, the authors refer the reader to the first chapter in (Cassandras and Lafortune 2007).

Systems of Ordinary and Partial Differential Algebraic Equations (ODEs, PDEs, and DAEs) are used to describe continuous time behavioral models. ODEs are often used to describe "lumped" systems while PDEs are used to describe distributed behavior (e.g., the traffic density along a stretch of road). Because it is often analytically or computationally intractable to use a truly distributed PDE, systems of ODEs arranged in a graph structure are often used instead. Bond graphs and linear graphs, for example, are well-known techniques that superimpose the constitutive laws of engineering physics onto the structure of a physical engineered system. Furthermore, pseudosteady-state assumptions are often made so that a subset of the differential equations are effectively replaced by algebraic equations to form differential algebraic equations as described in section "What is an Intervention?". Several software packages have been developed to simulate the systems of DAEs. These include Simscape by MATLAB, OpenModelica, and Dymola based on the Modelica language.

Agent-based modeling (ABM) goes beyond the dynamic laws of engineering physics to study socio-technical and socioeconomic systems. ABM leverages dynamic interactions between autonomous entities called agents (Bonabeau 2002). As the agents interact with each other, their individual processes and functions result in an emergent system behavior. This "bottoms-up" approach to modeling results in a number of benefits. ABM has the ability to predict emergent phenomena that often defy normal intuition. Furthermore, ABM provides a natural description of a system, especially for socio-technical systems in which individuals make decisions about their use of technical systems. Finally, ABM is flexible in that it can be expanded for the number of entities and their interactions. It also allows for changing levels of aggregation of agents in agent groups.

Discrete Time Behavioral Models

In contrast to the continuous time models, discrete time models are based on sampled data points or signals in digital form (Ogata 1994). The rise of digital information technology has increased the need for a deep understanding of discrete time behavior and the corresponding mathematics.

Models of engineering systems can be developed from theory using either continuous or discrete mathematics. However, whenever data is collected, discrete time models are the natural first choice. In either case, both types of models can be readily transformed from one to the other. In the case of linear systems, discrete time systems of equations can be solved algebraically with the use of the Z-transform in much the same way that continuous time systems can be solved algebraically with the Laplace transform.

The decision to use either continuous or discrete mathematics to model an engineering system depends primarily on the role of data and its discretization. In many cases, the data is intrinsically discretized, or the data collector has made pseudosteady-state assumptions that force discrete time stepwise evolution of algebraic equations. In other cases, data is not available, and so idealized differential equations can be used. Finally, digital systems are more accurately represented with discrete time models, and engineering physics are generally more accurately represented with continuous time models.

Discrete Event Behavioral Models

Discrete event behavioral models move from a time-driven view of the world to one that is *event triggered*. In such a case, the system remains in a discrete state until such a moment where an event causes the system to flip into another state. Many discrete event engineering systems exist, particularly as a result of automation where the underlying code is itself event-driven. Furthermore, discrete-event models always have discrete state that is usually denoted by integers (rather than real or complex numbers).

Automata are one type of discrete event model that are defined by a finite and countable set of discrete states that each represent some phenomenon (that is often qualitative in nature). This includes on/off states as well as hot/cold or red/yellow/green. These states are described by nodes. Meanwhile, arcs are used to describe the event triggers that allow a switching behavior from one state to another. These triggers can be either endogenous or exogenous rules but are often described by Boolean expressions (i.e., if $x \geq 0$, then switch from State 1 to State 2). While automata have deep roots in theoretical computer science, they have since found broad application in describing the operational behavior of many engineering systems that have an underlying discrete decision space. Automata are also often useful to describe operational modes of systems (e.g., normal, emergency, and restore) (Cassandras and Lafortune 2007). Despite these many strengths, the primary weakness of automata is that they have a centralized notion of state; and consequently all the states must first be enumerated in order for the complete automata to be well defined.

Markov models are a type of stochastic automata. They have been used to describe decision-making processes in a dynamic and stochastic environment (Sonnenberg and Beck 1993). Markov models have one of a finite number of states and stochastic events causing transitions between states. The evolution of state is tracked with each passing event or decision. Markov chains are a type of Markov model in which the probabilities of transitions are fixed over time. These Markov models can be used to support decision-making in that they can help to estimate the effects of a certain decision, including subsequent decisions of other actors in the system.

Petri nets are another type of (deterministic) discrete event model. Unlike automata, they have a decentralized description of state. In their simplest form, Petri nets consist of a set of places that define a state space, transitions that define events between a given pair of places, and a set of directed arcs that connect places and transitions (Cassandras and Lafortune 2007). In effect, these arcs create a *bipartite graph* between the sets of arcs and events. Furthermore, tokens are stored in places and are moved as each transition is "fired." The state of the system as a whole is described by a vector showing the number of tokens in each place. While Petri nets and automata have equal modeling power in that one can be mathematically transformed from the other (without loss), Petri nets can describe a relatively large number of automaton states with a relatively small number of places. Furthermore, because Petri nets are often represented graphically, they often lend themselves to modeling distributed engineering systems such as warehouses, manufacturing systems, or supply chains more generally. Finally, in recent decades, the Petri net literature has expanded to accommodate time-driven dynamics through timed and time Petri nets. They have also incorporated various types of stochasticity with stochastic and fuzzy Petri nets.

Hybrid Dynamic Behavioral Models

Hybrid dynamic behavior models combine the attributes of continuous/discrete time models with discrete event models (Van Der Schaft and Schumacher 2000). Generally speaking, they consist of a top "layer" described by either an automata or Petri net whose dynamics are either deterministic or stochastic. The bottom layer has a system of differential algebraic equations for each discrete state defined in the top layer. A classic example is the thermostat in a house. When the temperature is above a specified threshold, the heating system is idle. However, as soon as the temperature drops below the threshold, the heating system is activated and starts to heat the house. The model that is used to describe the "idling" state is distinct from the model that describes the "heating" state of the system.

Although hybrid dynamic systems have tremendous relevance to the understanding of engineering systems and their interventions, they remain at the cutting edge of systems research. First, hybrid dynamic models often rely on discipline-specific DAE models. Consequently, some researchers resort to strapping together multiple (often off-the-shelf) simulators within co-simulation environments. In other cases, researchers develop custom simulators in order to address the specific needs of the engineering system under study. The literature contains many such simulators (Allan and Farid 2015). Finally, from an analytical perspective, there is a severe lack of theory that combines both discrete and continuous states. Consequently, many of the typical analytical methods applied to continuous time systems (e.g., stability theory) or discrete event systems (e.g., reachability analysis) cannot be readily applied to hybrid dynamic systems.

Conclusion and Future Work

This chapter has provided an overview of engineering system interventions and their evaluation in an application-neutral language. It distinguished between interventions that change system behavior and those that change system structure. The type intervention dictates the type of evaluation and measurement that can be applied: be it experimental, data-driven, or model-driven. The chapter was brought to a close with a taxonomy of engineering system models including graphical, quantitative structural, and quantitative behavioral models.

In regard to the last of these, hybrid dynamic models, while complex, have the greatest applicability to the growing complexity of today's engineering systems. There is a profound need to develop engineering system models that capture both its continuous time and discrete event dynamics for the simple reason that engineering systems are continually changing structure while also evolving their system behavior. Such models grow our ability to practically study these engineering systems from a simulation perspective. That said, concerted theoretical effort can serve to provide deep analytical and generic insights into the structural, behavioral, and lifecycle properties of these systems.

The recent COVID-19 pandemic has highlighted the need for a deep understanding of both the technical and the social side of engineering systems. The engineering aspects of the dynamics of the pandemic are well understood. For example, the global transportation system has enabled the virus to spread rapidly over the globe. However, the impact of human behavior as part of social interactions is still unclear. Based on experiments and data collection, scientists have tempted to infer how the virus is most likely to infect other humans. The interaction between the well-understood technical side of the pandemic and the poorly understood social (human) side can be accurately represented by a hybrid dynamic model.

In addition to hybrid dynamic models, hetero-functional graph theory provides an avenue to investigate the ***complete*** structure of an engineering system. Such an approach does not require the extensive effort that is often needed to develop simulations of hybrid dynamic systems. Instead, UML/SysML models can be straightforwardly developed and then instantiated and translated automatically to produce hetero-functional graphs. In recent years, the network science community has provided an explosion of computational results over (traditional) graphs. There is great potential to apply similar approaches to hetero-functional graphs and capture the true heterogeneity found in modern engineering systems.

Cross-References

► Designing for Emergent Safety in Engineering Systems
► Dynamics and Emergence: Case Examples from Literature
► Engineering Systems Design Goals and Stakeholder Needs
► Engineering Systems Integration, Testing, and Validation
► Formulating Engineering Systems Requirements
► Properties of Engineering Systems
► Technical and Social Complexity

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Part IV

Reflecting on Engineering Systems Interventions

24 Research Methods for Supporting Engineering Systems Design

Zoe Szajnfarber and David A. Broniatowski

Contents

Abstract

Engineering systems, with their technical and social, cyber, and physical components interacting, are best understood when studied from multiple methodological lenses simultaneously. However, since different methodological paradigms have grown up in different disciplinary traditions, it is often challenging for researchers to draw on insights across them. In this chapter, we review four methodological paradigms of research done on engineering systems:

Z. Szajnfarber (✉) · D. A. Broniatowski
Department of Engineering Management and Systems Engineering, The George Washington University, Washington, DC, USA
e-mail: zszajnfa@gwu.edu; broniatowski@gwu.edu

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1. Quantitative observational research, including inferential statistics and machine learning
2. Qualitative observational research, which infer causal mechanisms based on deep contextual understanding
3. In vivo experiments and quasi-experiments, which manipulate theoretically motivated variables in more or less controlled settings to establish causality
4. In silico experiments, which deductively explore the consequences of a mathematical representation of reality

Each of these paradigms is increasingly common in engineering systems research. We compare the different types of conclusions one may draw from these techniques, with a specific focus on the ways they seek to guarantee validity, allowing us to assess their strengths and weaknesses with respect to engineering systems research. Our hope is that by providing a common framework for interpreting research results across diverse methods, more engineering systems researchers will feel comfortable building on results obtained through diverse approaches.

Keywords

Engineering systems · Full-cycle research · In silico experiments · In vivo experiments · Qualitative research in engineering · Quantitative research in engineering · Validity

Introduction

Engineers design and build systems to achieve practical goals (Broniatowski and Tucker 2017). Design reflects intention: the system's designer expects that a given intervention will lead to an intended outcome. For example, the designer of a power plant may build in a switch that, when flipped, will cause a pump to operate, cooling the system. This reflects a *causal* theory about the way the system will work (Moray 1990; c.f. Wacker 2008). Engineering is built on the application of causal theories, many of which are so well established that it is easy to forget the process through which they were discovered.

The discipline of engineering systems reaches beyond typical engineering theory and applications. Following the definition by de Weck, Roos, and Magee (2011, p. 31), the term engineering systems refers to

A class of systems characterized by a high degree of technical complexity, social intricacy, and elaborate processes, aimed at fulfilling important functions in society.

Examples of engineering systems include a power grid – both the technical infrastructure and the algorithms and humans that operate and use it – or an urban mobility system – composed of ground infrastructure, multiple vehicle classes, and the people and organizations who manage it and use it. As a result, in addition to the technical interactions within the system, understanding the system's behaviour requires consideration of the human designers and the social and organizational systems with which the system will interact once deployed. Causal theories that explain both social and technical interactions are less well established and are a substantial area of focus within the engineering systems community.

Given this emerging state of our understanding of modern engineering systems, how are we to know if a proposed design will perform as intended or if a proposed intervention on an already fielded system will result in the desired change? This chapter begins with a survey of research methodologies used to answer this question and then compares these methodologies in terms of their strategies and comparative advantages for achieving *validity* – the "approximate truth" of a proposition (Trochim 2006). As the field of engineering systems increasingly covers systems that are simultaneously social and technical, as well as cyber and physical, researchers are increasingly drawing on established methods from other disciplines, spanning the social sciences to computer science. No one methodological approach is suitable for answering all questions of interest to the community, and, in fact, most research questions benefit from study through multiple lenses. Therefore, it is increasingly important to understand standards of validity across approaches and also the relative strengths and weakness of each. Our review aims to provide a basis for doing this.

To illustrate the need for – and relative strengths of – using multiple methods to understand an engineering system, consider a city's urban mobility system. The availability of GPS locations from travellers' cell phones enables unprecedented network modelling of transit behaviour. Knowing patterns of use supports key decisions about, for example, infrastructure needs. However, while it paints a detailed picture of the current state, and careful quasi-experimental design can enable inference about user response to past disruptions, these techniques are limited in their ability to predict how users will respond to the introduction of new policies. For that, behavioural observations (e.g., conjoint surveys) are more appropriate, since they probe the decision-making process more directly. In addition, in most cities, planning around urban mobility is a multi-stakeholder problem. In the city of Los Angeles (LA), for example, different governmental entities control traffic lights, bus routes, and rails, not to mention right of way through the many interconnected municipalities that make up greater LA. As a result, any change is a strongly political process, with political dynamics playing at least as strong a role as any new vehicle technology. Qualitative methods are particularly adept at mapping and interpreting these types of dynamics. Effectively designing and implementing a new mobility system requires an understanding of all these inputs, making it critical to understand the range of methodological approaches available.

As summarized in Fig. 1, we divide the range of available research methodologies into two broad categories: the observational – in which we seek to define, explain, and/or predict existing relationships or patterns in their operational context – and the

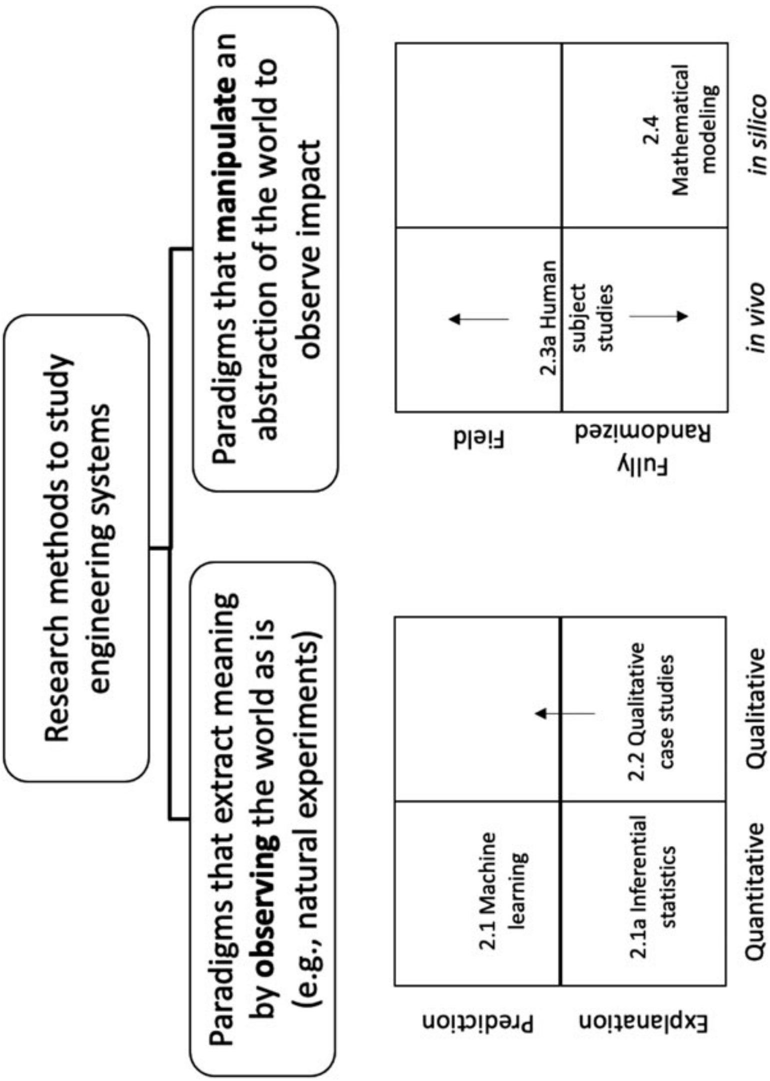

Fig. 1 Overview of research paradigms reviewed in this chapter

experimentally manipulated, in which we seek to explore the causal consequences of a given manipulation (or treatment) within a somewhat controlled environment. Within observational approaches, we treat qualitative and quantitative research methodologies as separate paradigms. In general, qualitative methodologies tend to take an inductive approach to inferring mechanisms from messy, unstructured, human data, while quantitative methodologies more often embody deductive analyses of explicit sensor data. However, as will be elaborated in the below sections, there is a spectrum of mixed methods in between, including inductive quantitative methodologies (e.g., unsupervised machine learning).

Within the experimentally manipulated paradigm, we separate in vivo experiments, where "treatment group" human subjects are observed performing tasks relative to a control group, from in silico experiments, where formal models are implemented in computer code with particular parameter values explicitly manipulated. In this paradigm, an abstraction of the world is observed and actively manipulated by the observer. The specific paradigms vary in terms of which components are natural (e.g., an actual human subject vs. a mathematical representation of a human making decisions) and how comparable the control group is to the treatment group. Each of these paradigms is broad and, as will be discussed, subsumes a large number of distinct methods. The bottom layer of Fig. 1 highlights the specific paradigms we will emphasize within this chapter. There are, of course, many other ways to organize this space (c.f., Robson 2002; Bryman 2016; Szajnfarber et al. 2020).

After providing a template for the process of doing research in each paradigm – framed in terms of the norms of that paradigm – we turn our focus to comparing the strategies each uses to ensure validity. Regardless of the method, analysis of engineering systems is inseparable from the process of making inferences. This is because, in order to generalize from our observations to next contexts, one must infer patterns from data and assume that these patterns will replicate in novel contexts.

Survey of Research Methodology Paradigms in Engineering Systems

Before comparing the strengths and weaknesses of the range of methodologies available to engineering systems researchers, this section first describes each of the four methodological paradigms separately. Each paradigm has its own strong methodological tradition and uses specialized language to define concepts rigorously. We therefore provide an overview and brief explanation of each tradition, before translating these key concepts into a common language that may be used by engineering designers. Since this is a broad review chapter, our treatment of each method is necessarily brief. Readers are referred to more comprehensive sources, including a special issue published in the *Systems Engineering Journal* in 2017 (Broniatowski and Tucker 2017; Grogan and Maier 2017; Panchal and Szajnfarber 2017; Szajnfarber and Gralla 2017).

Quantitative Observational Research: Inferential Statistics and Machine Learning

Classical quantitative observational research relies on applying inferential statistics to test whether hypothesized patterns in a given dataset are likely to be present or whether the observations may be attributed to probabilistic variability (see Casella and Berger 2002, for a classic treatment). Given a dataset and a theoretically motivated hypothesis, one may test whether observations are distributed as expected using a statistical *hypothesis test*. The test used depends on the nature of the data and one's assumptions regarding its underlying probability distribution. For example, if one can reasonably assume that the error in a given dataset follows a Gaussian probability distribution, then one may use techniques in the generalized linear model family, such as analyses of variance (ANOVAs), linear regressions, etc. Upon applying such tests, one typically obtains two parameters: an *effect size* and a *significance value* (also known as a p-value). The p-value indicates the probability of the data observed given the "null hypothesis" that there is no pattern that can be observed. Since our aim in applying inferential statistics is to rule out the possibility that any observed pattern is due to chance, smaller p-values indicate that the null hypothesis is less likely and that, conversely, an "alternative hypothesis" – i.e., that the observed pattern is not due to chance – is more likely. Separately, the effect size (e.g., regression coefficients in a regression model) provides a quantitative estimate of the strength of that pattern. Studies that have large, and significant, effects indicate that the theorized effect can provide a better explanation for the patterns observed in the data when compared to the null hypothesis. Notably, observation alone does not allow one to draw causal conclusions about how an observed pattern came to be, only that the data observed are highly unlikely to be due to random noise.

The theoretically motivated nature of inferential statistics makes it inherently interpretable yet at the potential cost of predictive accuracy (e.g., if effect sizes are small, yet significant). For example, one might theorize that a city's public transportation system's ridership is a function of socio-economic status, with higher-status individuals more likely to drive cars and lower individuals more likely to use public transportation. An inferential statistical model may show that there is an effect – i.e., that higher-status individuals are indeed more likely to drive cars, thus providing support for the hypothesized relationship. However, this effect may be small (e.g., higher-status individuals may only be 2% more likely to do so, explaining only a limited amount of variance in the data). Additionally, there is the possibility that investigators might *overfit* data without adequately controlling for multiple hypothesis tests (e.g., when one tests for the effects of several variables without an explicit theoretical motivation but only reports those that are statistically significant; so-called *p-hacking*) – a practice that some have theorized underlies the current "replicability crisis" in social psychology (Yarkoni and Westfall 2017). Furthermore, theoretically motivated hypotheses are not always available, especially in new situations.

In contrast, machine learning is an approach to quantitative observational research that is driven entirely by attempts to make specific predictions independent of explanation (for an excellent discussion of the difference between these paradigms, see Shmueli 2010; Yarkoni and Westfall 2017). Machine learning draws on quantitative sources of evidence and especially very large structured and unstructured datasets and takes an inductive or abductive approach to mathematical model building for the purposes of prediction (classic texts include Bishop 2006; Murphy 2012). For example, one might try to use an algorithm to estimate transit ridership. Machine learning is typically broken down into two types: *supervised learning* trains a model to learn from examples and make predictions on new data (further subdivided into *regression* – making continuous predictions – and *classification*, making discrete predictions), and *unsupervised learning* identifies latent structure in an existing dataset (for an excellent online resource, see Pedregosa et al. 2011). Here, a supervised algorithm might be fit to previous years' transit data to make predictions about future ridership statistics. Specifically, a regression algorithm might try to predict actual ridership numbers, whereas a classification algorithm might be useful in differentiating discrete "on-peak" versus "off-peak" time periods. In contrast, an unsupervised algorithm might be fit to the same dataset to provide information regarding which data are most strongly associated with ridership (e.g., price, number of transfers, etc.) In this chapter, we will focus primarily on supervised learning, since unsupervised learning does not claim to make predictions. Machine learning research ensures validity through prediction. The basic premise is that if a model is trained and tested on enough data, it should continue to predict on new data. Thus, this approach promotes replication over depth, with the researcher requiring very little contextual knowledge beyond what is required to select the right dataset and data features. Often, a machine learning researcher will try several different families of mathematical models on the same, *training*, dataset to determine which one provides the best fit. For example, given a dataset of ridership statistics from 2010 to 2019, one might train a model on data from 2010 to 2018. Once a family of models is selected, a single model is "trained" – generally by selecting model parameters to optimize some measure of performance on the training set. This final model's quality is then tested on a holdout set (e.g., data from 2019). If the model's performance is adequate, one might then rely on it to predict unseen data (e.g., 2020 statistics).

Thus, machine learning model's focus is on finding the best fitting model that can predict quantities of interest best, independent of explainability (although see recent attempts to introduce explainability into AI; Core et al. 2006; Doshi-Velez and Kim 2017; Gunning 2017; Samek et al. 2017). For example, a ridership prediction algorithm might produce very accurate estimates, but the reasons for this accuracy may be unknown. In general, such quantitative observational research is most valuable relatively late in the research value chain, when there is well-defined knowledge regarding what measures are most appropriate for a given outcome. Inferential statistics are especially useful when one already has a theorized mechanism regarding outcomes, whereas machine learning is especially useful when one can identify and predict specific measures. In both cases, testing system performance (either against an existing understanding or existing measures) takes precedence over building new understandings of the system.

The above discussion indicates that inferential statistics and machine learning are two classes of quantitative observational techniques that emphasize explanation and prediction, respectively. Table 1 summarizes the process steps involved in implementing techniques from this paradigm.

Table 1 Process of doing quantitative observational research

Process step	Key considerations
Choosing to employ quantitative	Quantitative research is most helpful when (1) large amounts of data are available; (2a) inferential statistics are most helpful when the priority for research is determining whether a theorized relationship can explain patterns observed in data; (2b) machine learning is most helpful when making predictions rather than understanding the phenomenon of interest
Defining a research question and focus	Quantitative research begins with a design goal – e.g., building a model that can predict a phenomenon of interest; thus, the focus is on identifying features in the data that explain or predict the dependent variable of interest. Machine learning models seek to take those features as input and generate accurate predictions, whereas inferential statistics seeks to estimate effect sizes to determine whether one or several competing theories can explain observed patterns
Selecting modelling approach	Given observed data, the researcher must decide which features should be treated as continuous and which as discrete/categorical and what is the most likely model to make predictions. The performance of several of these models can be compared using standard metrics error
Parameter selection	Model parameters are chosen to optimize performance on one (in the case of inferential statistics) or several (in the case of machine learning) training datasets. Inferential statistics evaluates the fit of these parameters using goodness-of-fit metrics such as R^2, the Akaike information criterion, etc., whereas machine learning models are then evaluated against test datasets and, if necessary, refined
Evaluation	Inferential statistics evaluates a model according to its p-values and effect sizes on the same dataset upon which the model was initially fit. In contrast, machine learning evaluates a model's predictive power on a holdout dataset which contains data that are not included in either training or test datasets. Evaluation metrics are selected based upon design goals and the specific outcome variable type (discrete or continuous)
Deployment	Once a machine learning model performs adequately on holdout data, it is deployed to make predictions. In contrast, inferential statistics are typically used to disconfirm theories with the intent of seeking the most likely explanations for data. Theories that survive this process of disconfirmation are used to make predictions

Qualitative Observational Research: Case Studies

Qualitative research is a paradigm that (a) examines a phenomenon in a natural or near-natural setting; (b) draws on non-quantitative sources of evidence, such as interviews, observation, or archival documents; and (c) typically (but not always) takes an inductive approach to inference and theory-building. It is important to realize that there are many variations on qualitative methods, including case studies (Eisenhardt 1989; Yin 2009), direct research (Mintzberg 1979), process tracing (Langley 1999; Van de Ven et al. 2000), and ethnography (Van Maanen 2011), among others. Szajnfarber and Gralla (2017) provide an in-depth review of qualitative methods in engineering systems. Returning to our urban mobility example, imagine that city planners were surprised to observe that a reduction in ticket prices has no impact on ridership in the most socio-economically depressed regions of LA. They wanted to understand why this had happened, so that they could improve future interventions. This is an instance where a qualitative study may be appropriate. Researchers would conduct interviews with a sample of riders in the specific neighbourhoods of interest, asking consistent but open-ended questions of how they use public transit. They might start with a convenience sample, speaking to customers at a corner store, and expand their sample through that initial population by snowball sampling. This style of sampling is appropriate when a population is difficult to enumerate and hard to reach as is the case with the *hard to count* population in LA. By building trust with interviewees and asking open-ended questions, the researchers might learn about factors they would not have considered. This population might not have options other than public transit to make long trips necessary to reach employment opportunities. Thus despite their poverty, they might be less price sensitive than other demographics. At the same time, the price cut might have no impact on discretionary rides since the prices are still too high for leisure in this population. This type of study could explain a puzzling observation and also characterize the important relationships that might be probed with later more cross-sectional work.

Table 2 summarizes the process steps involved in implementing a qualitative approach. Qualitative research ensures validity through depth of analysis (Eisenhardt and Graebner 2007; Yin 2009). The basic premise is that if a researcher sufficiently immerses itself in a case and collects *all* relevant data to describe it, they are able to rule out all potential alternative explanations for an observed effect in *this* setting directly. Achieving sufficient depth is directly at odds with replication. Typically a qualitative researcher will spend months to years studying a single setting (Mohr 1982, Langley 1999), and as a result most qualitative projects compare at most ten cases, usually closer to four (Eisenhardt 1989). This puts a strong emphasis on selecting cases for theoretical reasons to maximize potential for *analytical* generalizability (Yin 2009). In the above urban mobility example, building trust with the community is a key part of understanding the context of their answers and building theory from them. Moreover, since depth in particular neighbourhoods might be necessary, picking which ones to study will clearly have a strong impact on the generalizability of the results.

Table 2 Process of doing qualitative observational research

Process step	Key considerations
Choosing to employ qualitative research	Qualitative research is most helpful when (1) the phenomenon of interest is poorly understood, (2) the phenomenon can't be extracted from context, and/or (3) assessing impact of new tool/method in context
Defining a research question and focus	Qualitative research begins with guiding questions rather than precise hypotheses; questions may focus on identifying drivers and measures of system performance rather than improving it directly
Selecting cases	Case selection must balance (1) depth of information required to sufficiently understand each case and (2) breadth of intended generalizability. (3) it is often constrained by available variation
Scoping and conducting data collection	Data collection should (1) employ complementary types of data to understand all relevant aspects of a phenomenon and triangulate insights, (2) use appropriate sampling strategies, and (3) use well-established collection techniques for qualitative data
Analysing data	Analysis should follow established techniques for iterative within- and cross-case analysis, in order to abduce (hypothesize) tentative patterns; theory is validated through comparing patterns against new data from other cases
Interpreting results	Qualitative research yields explanatory theory for how and why systems behave as they do; it clarifies key relationships and defines how quantities can be measured, setting the stage for other methodological approaches that emphasize breadth

Qualitative research rarely attempts to make specific predictions. Its focus is on establishing relationships among variables of interest and providing plausible explanations for how they should interact in other contexts. Qualitative research is most valuable early in the research value chain, when there is a lack of theory explaining underlying system behaviour. The strong descriptive and explanatory lens provided by qualitative research makes it possible for more effective theory testing through other methodological approaches that are more appropriate for broader studies, as suggested in the mobility example.

In Vivo Experiments and Quasi-Experiments: Human Subject Studies

Methods focused on manipulation seek to establish that a theorized causal relationship exists and applies to one's intended context. The study of causal relations is fundamentally concerned with establishing that an *independent variable* (IV) – typically something that an experimenter can manipulate – causes a measurable change in a *dependent variable* (DV), typically something that reflects an outcome of interest while simultaneously controlling for covariates to rule out alternative explanations (for an introduction, see Box et al. 2005; Easterbrook et al. 2008; Maxwell et al. 2003; Seltman 2012). In our urban mobility example, an experimenter may be interested in determining whether a reduction in ticket prices – the IV – would increase mass transit ridership, the DV. *Randomized controlled trials* typically compare a treatment group to a control group, and subjects are randomly assigned such that, on average, any covariates are equally represented in these two groups, with only the independent variables differing between them. For example, one might recruit a large sample of human subjects and randomly assign them into two groups. Subjects in the treatment group would receive special metrocards that allow some money to be refunded at the end of the month, whereas those in the control group would receive standard metrocards. One might then compare the average frequency of mass transit use between these two groups. (When one is able to manipulate independent variables but unable to randomly assign subjects, these studies are called *quasi-experiments* – e.g., this might occur when retrospectively comparing samples of mass transit riders in two cities, which experienced equivalent price changes at different times; Campbell and Stanley 1963).

Beyond the process of selecting a research hypothesis and interpreting the results of an analysis, Shadish et al. (2002) define four types of research validity that guide experimental work. *Conclusion* validity refers to the extent to which one may infer a relationship in data that are gathered. For example, if one observes that riders who pay less use transit more often, is this difference statistically significant or is it due to random noise? Given conclusion validity, *internal* validity refers to the extent to which one may infer that the observed relationship is causal. In this experiment described above, a threat to internal validity may arise if subjects from the two groups compare the monthly prices of their transit fares, leading those with higher fares to use the system less often (e.g., because they feel cheated) and those with lower fares to use the system more often (e.g., because they feel that that is what those conducting the experiment "want to see"). *Construct* validity is concerned with how well the data gathered generalize to the theoretical constructs being studied. For example, a metrocard with a voucher sticker that refunds money at the end of the month may not accurately reflect the effects of a uniform decrease in price because riders would not see the savings at the point of purchase. Finally, *external* validity is concerned with the extent to which results generalize to new contexts. For example, results collected in New York City might not generalize to LA due to differences in transit culture. Each type of validity is established using specific techniques. These are discussed briefly in Table 3, which summarizes the process steps involved in implementing an experimental approach (see Trochim 2006).

Experimental research is fundamentally about testing explanatory theories that can make well-specified predictions (Shmueli 2010). Unlike inferential statistics and machine learning, the combination of explanatory and predictive power comes from reliance on a theory that has been tested in other contexts. To do so, it isolates a single or small number of causal relationships between independent variables and a single dependent variable in a context that is as tightly controlled as possible. Experimental research is most valuable when there are a small number of well-defined theories that make specific predictions system behaviour. The ability of a well-designed experiment to be used as a *critical test* to adjudicate between theories makes it ideal for isolating causal mechanisms underlying system behaviour (e.g., Birnbaum 2011). In the urban mobility example, a critical test might seek to

Table 3 Process of doing in vivo experiments and quasi-experiments

Process step	Key considerations
Choosing to employ experimental research	In vivo experiments are most helpful when (1) a well-defined theory can be identified relating independent variables to a dependent variable; (2) enough data are available to draw statistical inferences regarding the existence of this relationship; and (3) alternative explanations may be ruled out, allowing one to infer the existence of a causal relationship
Defining a research question and focus	In vivo experiments begin with a well-specified theory that enables one to draw precise hypotheses linking a cause or several causes to an effect. The causes should be linked to well-defined independent variables and the effect to a dependent variable
Sampling	The researcher identifies a theoretical population of interest to which one wishes to generalize. From this theoretical population, the researcher identifies an accessible population from which the study's sample is actually drawn. At each stage, sampling bias is carefully recorded and reported. These sources of bias, if uncontrolled, can undermine *external validity* – i.e., the extent to which the study results generalize to the theoretical population
Measurement	Independent and dependent variables are carefully assessed for their *construct validity* – The extent to which measures reflect theoretical entities of interest. Components of construct validity include convergent-discriminant validity – i.e., the extent to which a given measure correlates with other measures of the same construct and not with measures of different constructs – And reliability, i.e., the extent to which multiple instances of the same measure agree
Design	Ideally, experiments utilize random assignment to compare a control group to one or several treatment groups. The logic underlying random assignment is that, on average, groups should be statistically indistinguishable except for the manipulation controlled by the researcher. In practice, some *confounding variables* cannot be controlled for. In such cases, statistical controls may sometimes be used post hoc. When random assignment is not possible, the design is referred to as *quasi-experimental*, with subsequent threats to *internal validity* – i.e., causal inferences are weaker since more alternative explanations are plausible
Analysis	Experiments rely on sufficiently large sample sizes to draw statistically meaningful conclusions. *Conclusion validity* is the extent to which one might rule out sources of statistical error – Namely, false positives and false negatives – When inferring the existence of a relationship
Interpreting results	Experimental research, when properly conducted, generates unambiguous interpretations by enabling *critical tests* between competing hypotheses (e.g., a null and an alternative hypothesis or by adjudicating between two or more theories). Theories that do not adequately fit the evidence are generally discarded in favour of theories that fit better

adjudicate between price and access, e.g., by stratifying samples by socio-economic status (SES). Under this scheme, all members of a treatment group would receive the same price decrease, whereas a second treatment group would receive price decreases only if their SES was low. One could then compare high- and low-SES members of each group.

In Silico Experiments: Mathematical Modelling

Like randomized controlled trials, in silico experimentation is a paradigm that examines the causal consequences of a theoretical phenomenon. However, these consequences are explored through manipulation of a mathematical model, relying on a strictly deductive approach to experimentation. It is important to realize that there are many types of quantitative mathematical models, at different levels of abstraction or scales of analysis (Abbott 2006; Gershenfeld 1998). Furthermore, models also exist at different levels of theoretical abstraction with precise facsimile models seeking to represent the real world, whereas more abstract models aim to capture broad theoretical constructs in a qualitative fashion (Gilbert 2008). For example, microsimulation, game theoretic, and agent-based models focus on representing individual units and, in the latter two cases, their interactions. On the other extreme, system dynamics models and network flow models represent static interactions and average behaviours (see, e.g., Bonabeau 2002, for a discussion of the relative merits of each approach).

Table 4 summarizes the process steps involved in implementing a mathematical modelling approach to in silico experimentation. In silico experimentation is premised on model *verification* and *validation* (Carson 2002; Gilbert 2008; Robinson 1997; Sargent 2013; Thacker et al. 2004). Model verification is the process of ensuring that a model is implemented according to the intent of the researcher. For example, SUMO, an open-source urban mobility simulator, uses routing algorithms – such as Dijkstra's algorithm – to dynamically assign agents, representing vehicles, to routes between origin and destination locations (Lopez et al. 2018). Model verification, in this context, would be concerned with ensuring that the algorithm is correctly implemented (e.g., that Dijkstra's algorithm is implemented correctly and actually returns the shortest path). Techniques for verification include unit testing (e.g., ensuring that each routing algorithm works in isolation before the user has the chance to choose between them) and replication across multiple computational platforms (e.g., Windows vs. Linux) and by different users. In contrast, model validation is the process of ensuring that the model reflects reality in some sense, either by comparing model outputs with external data sources or by obtaining expert input for each component of model operation. Thus, models can be valid even if they are not directly evaluated against data. For example, when simulating traffic in LA, SUMO output might be compared to actual traffic patterns in LA. On the other hand, when simulating traffic on a random graph or another hypothetical structure, output

Table 4 Process of doing in silico experiments

Process step	Key considerations
Choosing to employ mathematical modelling research	In silico experiments are most helpful when (1) the phenomenon of interest can be represented a well-defined theory; (2) the theory can be implemented as a mathematical construct; and (3) all contextual factors that are assumed to be relevant can be included in the model itself
Defining a research question and focus	In silico *experiments* begin with a well-defined mathematical formulation or axioms; questions may focus on exploring the logical consequences of this formulation or on comparing the outcomes from different formulations
Model verification	Model verification is the process of ensuring that a model is appropriately implemented given a well-defined theoretical formulation. Typically, one verifies a model by translating the underlying theory into pseudo code, which is then implemented in a computational substrate by the modeller or other researchers
Model validation	Results and other output must be compared to some external standard in order to have confidence that the model accurately reflects the phenomenon of interest. To do so, one may compare model results to empirical observations, to experts' expectations, etc.
Sensitivity analysis	Once a model has been validated, the researcher must determine the range of parameters under which the model continues to deliver results that reflect the phenomenon of interest. Typically, one does this by systematically varying model parameters to determine how this affects outputs. In general, models with fewer parameters are considered more scientifically parsimonious and, thus, more likely to generalize
Interpreting results	In silico experiments explore the consequences of complex theories whose outcomes may not be immediately obvious without computation. It enables researchers to directly interact with model parameters to explore the consequences of manipulating these parameters in a simulated environment without requiring expensive experimentation in laboratory or real-world settings

must be compared to a user's expectations (e.g., derived from a mathematical theory, elicited from experts, or otherwise).

Research that employs in silico experimentation often attempts to make predictions. However, except for the most precise facsimile models, these predictions are high-level qualitative outcomes that must be interpreted loosely. Its focus is on probing the implications of relationships between variables of interest, especially when there are many such relationships with complex consequences. Mathematical modelling research is most valuable when some preliminary theories have been established but before decision-makers are willing to commit significant resources to test these theories. Models thus make it possible to examine the decontextualized consequences of several different theories at low cost, albeit with less generalizability.

Although each of the research paradigms has clear internal standards for methodological rigor, they each focus on different issues in ensuring research derived from their insights are valid. Additionally, since they are framed to deal with a particular kind of research question, it's important to recognize where each is best applied in the broader research value chain. Table 5 provides a summary of these points. In the next section, we build a common framework for thinking through validity across research methods.

Knowing What you Know: Assessing Validity

Causal theories are valuable if they can be trusted to inform decision-making when designing and testing interventions on engineering systems. While each of the above approaches to research differ in how they define quality, and correspondingly, validity, of the inferences they make, they fundamentally share the goal of generalizing from patterns observed in a *study context* to the *target system* of interest. We therefore adopt, while slightly expanding, the four key types of validity described by Shadish et al. (2002):

1. Conclusion validity: a relationship between X and Y is actually there and not due to random error (and that if it's there it would be observed).
2. Internal validity: the relationship is not spurious, namely, that X causes Y in the study context.
3. Construct validity: the way(s) that X and Y are measured in the study context reflect the concepts they aim to proxy.
4. External validity: inferences made about X and Y in the study context predict behaviour in the target system.

In the below sections, we discuss how each of the four methodological approaches establishes validity. Table 6 compares the paradigms.

Conclusion Validity: The Effect Is Actually there

If one seeks to generalize an observation, a key step is ensuring that the effect is actually there. This is often referred to as conclusion validity. A study can lack conclusion validity if it misses a relationship that actually exists (e.g., it lacks the statistical power to observe it) or because it identifies a relationship that isn't really there.

In quantitative observational methods, conclusion validity is directly measurable. Inferential statistics provide p-values and effect sizes that indicate the extent to which an effect is present. In contrast, a machine learning approach asks which of a range of available models best fits the data. For example, a machine learning algorithm might be designed to select the coefficients of a linear regression model or a specific separating hyperplane within the broader class of support vector classifiers.

Table 5 Strengths and weakness of surveyed methodological paradigms

Paradigm	Description	Best use	Cautions
Quantitative observational	Applies mathematical models to identify patterns in data to explain the data or predict quantities of interest on new data	When large amounts of data and computational power are available. Enables rapid assessment of many alternative models or hypotheses Applies to aggregate behaviours of either social or technical elements	Inferential statistics are subject to potential overfitting and confounding, whereas machine learning can generate prediction without explanation with limited insight into which contexts results will generalize. Generalizability depends on selection of theoretical constructs or holdout/test datasets
Qualitative observational	Leverages deep observation of a phenomenon in context to theorize about underlying mechanisms	Gaining traction on a new phenomenon. Rich description clarifies key variables and relationship among them Typically focused on human aspects of system	Labour intensive, limiting replication; generalization relies careful assessment of context similarity
In vivo experimental manipulation	Control for confounding variables to enable causal theory to be inferred from observation	When aspects of environment are controllable, best way to build causal theory Applies to both social and technical systems but statistical techniques differ depending on unit of analysis	Controlled environments must be carefully designed to capture salient characteristics of operational context, particularly in complex system. Relies on ability to match measures to theoretical constructs
In silico experiments	Build a fully simulated environment in which theorized relationships can be explored	When adequate theory exists for representing phenomenon, most flexible basis for exploring the impact of alternative scenarios. Models have been constructed for technical and social systems and their interactions	Conclusions are only valid to the extent that the theory reflects the phenomenon of interest in its context

This selection occurs by selecting from a small set of performance metrics – e.g., mean-squared error, accuracy, precision, perplexity, etc. – and then applying algorithms that select model parameters to optimize those metrics. For a given type of

Table 6 Comparison of approaches to ensuring validity across paradigms

Paradigm	Presence of effect	Causal claim	Right measures	Conclusions apply to?
Quantitative observational	*Quantitative performance metrics* determine best model	Observational data cannot serve as the basis for causal claims but must instead be used to disconfirm. However, there is an active area of machine learning that seeks to rule out confounds (Pearl 2018)	*Construct validity* applies to inferential statistics, but not to atheoretical machine learning; however, feature selection could be considered	*Inferential statistics* require assumptions about external validity or are limited to similar data (Trochim 2006). In machine learning, *holdout set performance* indicates whether models generalize to new data
Qualitative observational	Implicit: Strategies to rule out confirmation bias of observer	*Internal validity* achieved through depth of observation	Implicit: Triangulation among independent data sources	*Analytical generalizability* checked through replication logic
In vivo experiments	*Conclusion validity* relies on statistical significance of effect	*Internal validity* achieved through ruling out confounds	*Construct validity* through reliability and convergent/ discriminant validity of measures	*External validity* through representative sampling
In silico experiments	N/A since no data are measured except for the most precise, *facsimile models*	Causal relationship is guaranteed within the structure of the model by virtue of computational implementation	N/A since no data are measured; however, *model verification* seeks to establish correspondence between theoretical construct and model implementation	*Model validity* seeks to demonstrate generalizability to reference system, but scope of generalizability often not explicitly considered

machine learning task (regression, classification, etc.), metrics may frequently be compared across model families, meaning that one may select from among several different model families (e.g., logistic regression classifiers, vs. naïve Bayes classifiers, vs. support vector classifiers, vs. recurrent neural nets, etc.). An exciting new development in this area carries out this comparison and model family selection automatically (Le et al. 2020).

In qualitative observational methods, conclusion validity is rarely discussed explicitly but is still critical. Unlike in inferential statistical methods, which seek to test whether a hypothesized effect manifested, qualitative methods aren't typically looking for a particular effect. Instead, qualitative researchers uncover causal mechanisms by immersing themselves in massive amounts of data and systematically assessing whether the patterns they intuit are reflected in the broader data – an attribute shared in common with machine learning techniques. The notion that qualitative researchers deal with small datasets is a myth. As Pettigrew (1990) poignantly described it, the greater concern is "death by data asphyxiation". It is not uncommon for qualitative researchers to deal with tens of thousands of pages of documents, and there are currently neither algorithms nor statistical tests to assess conclusion validity in qualitative research. Instead, during this abductive process of generating propositions and testing them, researchers must carefully balance trusting their intuition and experience about the presence of potential patterns while not succumbing to confirmation bias. Many qualitative scholars have suggested strategies they use including mapping data and relationships in divergent ways (Miles and Huberman 1984; Eisenhardt 1989), enlisting independent coders to ensure that multiple raters would arrive at the same conclusion, or following a logic similar to maintaining a holdout set. Here, researchers focus their analysis on a subset of the case data and generate proposed patterns. These patterns can then be tested across the remaining dataset to see if they hold. In writing up qualitative results, it is important for researchers to "show" and "tell" enough of the chain of evidence so that the logic of their conclusion can be assessed by readers.

In in vivo experimental studies, conclusion validity is primarily assessed using the same standard statistical techniques used for quantitative observational studies. The putative relationships are typically inferred from experimentally generated data by conducting test that fit simple mathematical (e.g., binary comparisons, regressions, etc.) to the observed data using standard metrics of effect size, p-values, and error rates.

Finally, in in silico experimental studies, there is no need to ask this question, since there is generally no comparison between model output and data (however, facsimile models do aim to make precise estimates and are typically compared to data using measures similar to those used in machine learning and experimental paradigms). Rather, relationships observed are logical consequences of the model's structure. Since mathematical models aim to compare alternative interventions, given a common mathematical abstraction of the context, the relevant question is whether the effect of one intervention is different than another. Depending on the modelling style, this can be done categorically (often visually) or using standard statistical confidence intervals.

Internal Validity: The Effect Is Causal

Engineering relies on causal relationships to influence the behaviour of systems. The research result that X caused Y means that if I change X, it will have the intended, predictable, impact on Y, at least probabilistically in the specific context studied. In practice, except in a fully controlled experiment, where X is the only possible cause of the observed effect on Y, by design, best practice is to attempt to rule out as many alternative explanations as possible. The strategies for doing this differ across methodological approaches.

In quantitative observational studies, one may not infer causality (although see Pearl 2018; Pearl and Mackenzie 2018 for attempts to do so in machine learning). This is especially the case for inferential statistics, which cannot make causal claims except to the extent that an observed pattern accords with an existing theory. In machine learning, which is explicitly atheoretical, the underlying issue is handled in two ways. First, machine learning approaches pick the best of a large number of models that best describes the training data. Second, the approach assumes that given enough holdout datasets, confounding variables should, in theory, be removed from automated models. Nevertheless, a stream of machine literature has increasingly begun to recognize that, in practice, identifying whether a given holdout dataset is an adequate test is difficult without internal validity concepts. This is because there is no way to know when purely predictive techniques are prone to confounding (e.g., Lazer et al. 2014). In particular, the field of causal inference, within the machine learning community, seeks to automatically identify and control for major confounds and remains a major focus for future research.

In qualitative observational research, internal validity is addressed by attempting to achieve (near) complete observation. The basic premise is that if researchers sufficiently immerse themselves in a case and collect *all* relevant data to describe it, they are able to rule out all potential alternative explanations for an observed effect in *this* setting because they know it wasn't what happened. For this to be a valid argument, it is important to establish that the observation was comprehensive enough. While it is never possible to prove complete exhaustion, there are accepted guidelines for assessing completeness. First, when it isn't possible to interview and/or observe everyone involved in a case, typical notions of representative sampling must be adopted (Babbie 2004) when possible. However, in many qualitative contexts, even statistical sampling isn't feasible. In such situations, non-statistical sampling methods like snowball sampling techniques must be applied. Snowball sampling uses referral chains to identify subjects sequentially. To the extent possible, the chains should be initiated in as many independent sources as possible. It is considered acceptable to stop snowballing when several additional samples return no new information. This is called theoretical saturation. Second, whether seeding a snowball sample or designing interviews, it is critical to ensure that as many different perspectives are represented as possible. This often comes up when balancing interviews with managers, engineers, and technicians to learn all sides of the story.

In in vivo experiments, there is a distinction between quasi- and fully randomized experiments. Quasi-experiments are experimental scenarios in which randomization of at least one variable is lacking for a given manipulation; researchers use multiple complementary strategies to establish internal validity. They systematically anticipate potential confounds (see Campbell and Stanley 1966 for a standard list), removing them if possible through quasi-experimental design (e.g., by comparing otherwise similar contexts), controlling for them statistically if it is not possible to remove them, and finally, examining their plausibility for those that remain.

For example, one might argue that a proximity sensor, and not a switch, is responsible for cooling a system. However, if the switch also controls the system's power, then it is not plausible that the proximity sensor would be operational while the switch was off. Similar concerns apply to the use of inferential statistics on retrospective observational data, where only statistical controls, non-equivalent (and therefore, confounded) control groups, or appeals to plausibility may be used.

In in silico experiments, mathematical models are instantiations of causal theory. That X causes Y is given, because X causes Y by design as long as the causal relationship was implemented correctly in software or mathematical formulae. Confirming this is referred to as verification. While verification is conceptually different than the notion of internal validity, its function is analogous. In experimental settings, internal validity is the foundation of all inference, since if you're not confident that X caused Y, no predictions can be made and theories cannot be relied upon. Similarly, in mathematical modelling, all further analysis must trust that the theory being studied was instantiated correctly in the model. In order to answer this question, Gilbert (2008) identifies several strategies that are shared between model verification and software verification, including unit testing – the process of breaking model code into discrete chunks and testing these chunks individually – and replication, ensuring that a model operates the same way when implemented on different platforms.

Construct Validity: The Ways That X and Y Are Measured in the Study Context Reflect the Concepts they Aim to Proxy

It is a well-known maxim that "you get what you measure". In typical engineering contexts, we take for granted that when we, for example, read the value off a weight scale, that reading corresponds to the objects mass (when accounting for Earth's gravity). In the engineering systems contexts, when the constructs of interest tend to be less concrete – like a system's complexity or resilience – assessing construct validity becomes increasingly important. For example, despite significant scholarly effort to measure a system's complexity (Lloyd 2001; Summers and Shah 2010; Sinha and Weck 2016; Broniatowski and Moses 2016), there remains disagreement about the precise meaning of this term. A lack of correspondence between data and theoretical constructs limits the potential for studies to build on one another.

Quantitative observational studies typically have limited opportunity to establish construct validity. In the context of inferential statistics, the paradigm instead relies on the use of already established valid measures. Machine learning, on the other hand, is atheoretical and sees data as standalone "features", independent of the theories that they embody; therefore, construct validity is not discussed. Nonetheless, researchers make design choices about how to represent features – e.g., as discrete, continuous, ordinal, etc. – and these choices can have a strong impact on which model is selected.

Similarly, in qualitative observational research, construct validity is not typically discussed because the intent is to make a direct and complete measure of the construct in question. Nonetheless, qualitative researchers do discuss triangulating among data sources extensively (Yin 2009; Eisenhardt 1989; Langley 1999). For example, if the same construct (e.g., awareness of risk) is seen explained through retrospective interviews and corroborated by archival e-mails and design documents, the researcher can have much more confidence that the reported perception matches the subject's metal state at the time and also gives cues for how such a sentiment would show up in a format like an e-mail. Szajnfarber and Gralla (2017) provide an extensive discussion of the relative strengths of different types of qualitative data.

In in vivo experimental settings, construct validity is front and centre. Construct validity refers to the extent to which the actual measure (the number on the scale) actually reflects the theoretical construct (mass). In experimental psychology, there are two major components to construct validity: (1) reliability and (2) convergent-discriminant validity (other aspects of construct validity, such as face validity and predictive validity, are also discussed by Trochim 2006; however, we omit these for brevity).

Reliability. The reliability of a measure refers to the extent to which it can be replicated. For example, if two engineers apply the same technique to measure a system's complexity, will they get the same result? What if the same person applies the same measure to the same system, but at two different times? There are two specific types of threats to reliability: (1) measurement bias, which may result from systematic sources of error in a measurement, and (2) random error, which may result from variance in the measurement itself. A measure is reliable if it is both unbiased and low variance.

Convergent-Discriminant Validity. One can demonstrate the validity of a measure by showing that it agrees with other measures of the same construct and also disagrees with measures of unrelated constructs. For example, if weight is a measure of an item's mass, then weight should also be associated with the item's moment of inertia and its kinetic energy – both also a function of mass. Thus, weight, inertia, and kinetic energy should all be strongly correlated. This is *convergent validity.* In contrast, one should not expect an item's weight to be correlated with its colour. Thus, these measures should display *discriminant validity.*

Within the in silico experimentation tradition, model verification is concerned with the match between the model's implementation and the modeller's intention. However, traditional notions of model verification don't take into account concerns regarding whether the modeller's intended implementation matches the underlying theoretical construct. We contend that a notion akin to construct validity should be explicitly considered as well. Consider, for example, a model that aims to assess which aspects of product interconnectedness most impact its complexity. The modeler would draw on a theory of what complexity is, for example, embodied in a measure that takes complexity to be a function of the number of process steps needed to instantiate the system (Summers and Shah 2010), as well as process theory relating product features (including interconnectedness) to the process of doing work to instantiate the product. Verification is concerned with whether the model accurately reflects the intent of the model designer (regardless of whether the model designer's intent is an accurate description of the theory). Construct validity is concerned with whether the theory is accurately represented by the designer's intended implementation. Model validation is concerned with whether the model's outputs accurately predict real system performance. Finally, construct validity is concerned with whether the definitions of a process step in the model, and the measures of process steps in the real world, correspond to the theoretical definition of complexity. Since the modeller aims to make a prediction about how increased interconnectedness impacts complexity, it also matters whether counting steps is related to the construct of complexity. This issue is rarely made explicit in modelling studies, and there's an opportunity to clarify this relationship in light of the concept of construct validity from experimental studies.

External Validity: Conclusions Drawn from the Study Context Generalize to New Data/Contexts

Ultimately, the reason for doing research is to be able to use knowledge gained in one context to gain insight, and perhaps make predictions, in new contexts. In engineering systems contexts, this notion is interpreted at two levels. The first level of external validity asks if causal inferences made on a sample (e.g., 100 engineers from a large organization) would hold if the study is repeated on a different sample (e.g., a different 100 engineers from that same organization). This is a question of statistical generalizability and hinges on whether the sample is representative of the population. The second level of external validity asks to what other contexts those causal inferences would apply. Would the same inference replicate in another organization? This is a question of analytical generalizability and isn't amenable to formal statistical tests (Yin 2009). The same concept has been discussed by Trochim (2006) as a function of "gradients of similarity" between the study context and the context to which the researcher would like to generalize. Depending on the research approach, the case for external validity is made by replicating the study across multiple divergent contexts or through careful logical argument for the basis of similarity across contexts.

For quantitative observational data, one does not strictly speaking seek to generalize, so much as to explain the data in a post hoc manner. The explanations may generalize to the extent that the underlying theoretical constructs have been demonstrated in other contexts. Thus, external validity of these studies is more a function of the theory than the specific dataset which cannot be generalized (beyond arguments about plausibility) because of inability to rule out confounds. In contrast, in machine learning, after a model has been fit to training data, its final quality is assessed on "holdout data" – i.e., data that have not been included in training or test sets and therefore represent a novel context. To the extent that the holdout data are similar to the training and test data, we might expect similar performance; thus, holdout results have some commonality with the establishment of *external* validity in that they represent the extent to which a machine learning model's results replicate to new data. Machine learning analysts don't typically consider the logic for how the training and holdout test datasets were selected, and this obviously has a strong impact on generalizability. Rather, machine learning researchers may retrain models when holdout performance decreases and as new data become available.

In qualitative observational research, external validity is achieved through analytical generalizability. Yin makes the analogy to experimental research where a case corresponds to a single experiment; researchers build confidence in the external validity of their experimental results by replicating it under new conditions. He argues that it is inappropriate to think of a single case as a single "N" (Yin 2009). It is better thought of an instance of the world that embodies complex interactions among subjects, tasks, and context. Therefore, researchers must choose their set of cases for theoretical reasons, to ensure capacity to generalize along the intended dimensions. There are two main strategies: (1) replication logic and (2) natural experiments. Replication logic seeks to build confidence in the external validity of one's findings by performing additional case studies, with each intended to perform either a literal replication (where the results should be the same) or a theoretical replication (where the results should be predictably different). Choosing cases in this way requires that the logic for how each additional case is similar or different – based on underlying theorized causal mechanisms – is critical. Where a replication logic strategy can pick each next case to corroborate or extend findings from the previous instance, a natural experiment strategy must pick all cases up front. Here, researchers identify situations where the natural variation in the world produces a near experiment and take advantage of it. In both cases, clearly articulating the logic for why the researcher believes the inferences made in the relatively small number of case studies apply to other classes of context is critical.

In in vivo experiments, this question depends on whether the theory that was the basis for designing the experiment generalizes. Traditionally, external validity is established by ensuring that the data within a given experiment is a *representative sample* of a population. One ensures that a sample is representative by measuring the statistical distribution of quantities of interest in a population – typically those quantities that are expected to affect the generalizability of the results – and then recruiting subjects with characteristics that have the same distribution. If the sample is representative, this implies that the results of the study should generalize to the population. Trochim (2006) notes that it is not always possible to ensure that a sample is representative and, instead, judges the external validity of a study by the *proximal similarity model* – just as, in a quasi-experimental design, one can argue that confounds are implausible, one can make a case for external validity by arguing that the study's sample is *similar to* the context to which the study aims to generalize. Thus, comparing the sample's characteristics to those of the intended target population and evaluating the ways in which they differ may establish external validity. In many engineering systems applications, the subject-task and possibly subject-task-context interaction must also be representative (or similar), since many engineering tasks are contextually driven. For example, an experienced engineer tends to behave like a novice (or worse) when faced with different tools and different types of problems.

In in silico experiments, the approach to assessing how far results generalize depends on the level of fidelity of the model. These approaches are generally referred to as validation. In high fidelity models, the model output is compared to data from the reference system to assess outcome correspondence. In more abstract models, outputs are assessed against categorical expectations, rather than against specific data. In such cases, model validation is generally assessed by expert opinion and may therefore also have some similarity to some aspects of *construct* validity – namely, *face* validity. However, in both cases, the comparison is to a reference instance in the world and not other contexts. Since mathematical models instantiate a theory and explore implications within that framework, similar to analytical generalizability or proximal similarity, their conclusions should apply to all other instances that the theory does. Furthermore, the generalizability of a mathematical model is a direct function of its level of abstraction, with more abstract models more likely to generalize to more contexts, but only with qualitative or categorical predictions. In contrast, more precise, facsimile models may handily predict outcomes in a very specified context but may not generate the same predictive accuracy for other contexts in which initial parameter values may no longer fit.

Summary

The future of engineering systems research is interdisciplinary, like the systems studied. Advancing new theory and assessing predictions about how systems will behave will require insights from multiple different approaches. In this chapter, we provide an overview of four different – and increasingly adopted – paradigms to developing and assessing predictions made about engineering systems. There is no best method for studying all systems in all contexts. This chapter provides guidance for which method is most likely to provide insight depending on the state of existing theory and the quality and nature of available data. We emphasize that regardless of the method chosen, the nature of its predictions, and the threats to confidence that one may have in them, depends crucially on the accompanying standards of validity. To that end, we provide a template for evaluating the quality of the claims made across methods, based on validity concepts appropriate to the method used.

So far, research across these methodological paradigms has remained relatively segregated, partially because validity concepts are discussed so differently. This review has taken a first step to providing a common basis for understanding their insights so that they can be used as complements vs. in competition.

Cross-References

- ▶ Asking Effective Questions: Awareness of Bias in Designerly Thinking
- ▶ Design Perspectives, Theories, and Processes for Engineering Systems Design
- ▶ Educating Engineering Systems Designers: A Systems Design Competences and Skills Matrix
- ▶ Engineering Systems Integration, Testing, and Validation
- ▶ Formulating Engineering Systems Requirements
- ▶ History of Engineering Systems Design Research and Practice

► Human Behaviour, Roles, and Processes
► Properties of Engineering Systems
► Risk, Uncertainty, and Ignorance in Engineering Systems Design
► Roles and Skills of Engineering Systems Designers
► Technical and Social Complexity

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Transforming Engineering Systems: Learnings from Organising Megaprojects

25

Joana Geraldi and Andrew Davies

Contents

Abstract

Whether through the delivery of a sewage system or energy distribution system, megaprojects are designed to intervene in engineering systems in a purposeful and deliberate manner. Although they always transform the system, their impact is partly predictable and partly unknowable. While the uncertainty surrounding megaprojects is widely accepted in practice and literature, project achievements are still compared against planned goals, and megaprojects are declared to be over budget, over time, over and over again, Flyvbjerg poignantly insists. Why is it so hard to design, deliver, and yield long-term benefits from megaprojects? Grounding our work in project studies literature, we discuss four challenges involved in managing megaprojects: (1) delivering purposeful interventions, (2) integrating complex work under high levels of uncertainty, (3) collaborating with friends and

J. Geraldi (✉)
Department of Organization, Copenhagen Business School, Copenhagen, Denmark
e-mail: jge.ioa@cbs.dk

A. Davies
SPRU, University of Sussex Business School, Brighton, UK
e-mail: andrew.davies@sussex.ac.uk

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foes, and (4) innovating and learning under high time and budget constraints. The chapter offers implications for practice and research at the intersection between engineering systems and megaprojects.

Keywords

Complexity · Decision-making · Engineering systems · Innovation · Integration · Megaprojects · Project studies

Introduction

Engineering systems are socio-technical systems aimed at fulfilling important functions in society, such as healthcare, transportation, energy, etc. (de Weck et al. 2011). Like living entities, they continually adapt to changing social, financial, and environmental conditions. As such, engineering systems are never completely designed from scratch and are "never quite finished" (Hirschman and Lindblom 1962, p. 217). Megaprojects are widely used vehicles for designing large interventions in engineering systems to adapt systems to changing conditions. This chapter explores some of the actual practices and challenges involved in managing megaprojects.

We understand megaprojects as "large-scale, complex ventures that typically cost US$1 billion or more, take many years to develop, build [and implement], involve multiple public and private stakeholders, are transformational, and impact millions of people" (Flyvbjerg 2014, p. 6). Such projects are different from smaller projects, not only simply in terms of their sheer size but also due to their complexity, uncertainty, and transformative effect on society. As a result, the management of megaprojects requires distinct knowledge and capabilities (Morris 1994); if managing projects were comparable to driving a car, megaprojects would be like flying a jumbo jet (Flyvbjerg 2014).

We propose a view where megaprojects are vehicles for intervening in engineering systems, triggering social and technical transformations that are partly foreseen and partly unforeseen (de Weck et al. 2011). Managing megaprojects is notoriously hard. The field of project studies has a stream of research focused only on success factors that aim to identify conditions and management techniques that are more likely to contribute to a successful (mega)project (Söderlund 2011), such as project sponsor support and realistic budget and schedule estimations. Yet, the studies on success factors may point to the wrong lessons, as they base the understanding of success on the difference between planned and actual delivery (Kreiner 2020). For example, if successful projects are delivered according to estimations, then accuracy in estimations becomes a relevant factor. However, empirical studies suggest that projects might meet and exceed stakeholders' satisfaction and promote beneficial transformations in engineering systems while not actually meeting their expected budget and delivery time (Ika 2018). Thus, meeting the plan and delivering a positive impact in engineering systems appear to be independent factors. Therefore, contrasting the normative literature in the field, we explore the actual management of megaprojects and debate the concept of megaproject success from the perspective of its intervention in engineering systems. We start the chapter by discussing the notions of project management and of success in order to provide a more nuanced and realistic view of a megaproject's actual challenges. We then explore four main challenges involved in managing megaprojects and the approaches for tackling these challenges proposed in the literature or observed in practice.

Managing Megaprojects as Temporary Organisations

This section is dedicated to defining managing megaprojects. We start with a critical look at the common methodology for managing projects and propose a view of projects and project management as temporary organisations. We discuss the implications of this perspective and nuance its meaning in this chapter.

Megaproject management (just as project management) has been wrongly equated with a managerial methodology that is based on classic project management tools and processes, typically represented in scheduling techniques (Geraldi and Lechler 2012). The overall principle behind this methodology is to design plans and requirements upfront and to execute the plans. This form of managing has been criticised for, among other things, focusing on project execution over its strategic framing (Morris 1994), failing to adequately address human intricacies of projects (e.g., Nicolini 2002; Crawford et al. 2006), being too rigid to deal with the changing conditions of projects (e.g., Kreiner 1995; Williams 2005; Wied et al. 2020a), and failing to incorporate learning developed throughout the project (Pich et al. 2000; Sommer and Loch 2004). Moreover, this methodology assumes that project owners and other project actors *can* define upfront what is required to intervene in an engineering system to create intended benefits. However, practice shows otherwise: projects may extend in time and budget (Ika 2018), and the delivered outputs do not guarantee the desired project outcomes and benefits (Kreiner 1995). Limiting project management to only one methodology constrains both the learning from the actual project management practices and the development of different management approaches.

One alternative is to consider this methodology as a form (but not the only one) of managing projects and adopt an umbrella concept that encompasses different approaches and levels of management in, on, and for projects (Morris and Geraldi 2011). We found such an umbrella concept through understanding projects and their management as temporary organisations (Lundin and Söderholm 1995). In the following paragraphs, three implications of this view of project management are discussed in terms of organisational effort, temporality, and purposefulness.

Box 1 The London 2012 Summer Olympics

The London 2012 Summer Olympics is a rare example of a megaproject and an Olympic Games that finished on time and *below* budget, at least according to its latest baseline. The initial budget anchor was £2.3 billion, *despite* Beijing (2008) costing £9.8 billion *and* Barcelona (1992) costing £8.06 billion. The

(continued)

Box 1 (continued)
baseline was reconsidered in the following years; in 2002, ARUP (an architecture and construction firm) estimated the budget at £1.8 billion, which was corrected in 2003 to £3.14 billion by PwC (a consultancy firm). In 2004, the bid submitted for evaluation of the Olympic Committee suggests a budget of £4.21 billion, and finally, in 2007, the National Audit Office completed the official estimation of £9.3 billion. According to the UK Department for Culture, Media and Sport, the total actual cost was £8.92 billion – below the official and detailed estimation (Pinto 2013). The project had high expectations. London was awarded the right to host the Olympics based on a promise of a sustainable legacy for London and the UK, which involved maximising the economic, social, and environmental benefits of the Games. In particular, this occurred through the regeneration of East London, which was, at the time, a troublesome neighbourhood, and improvement of elite and grassroots sport performance in the UK (Pellegrinelli et al. 2011). Next to the long-term aspirations, the project involved a complex intervention in London, including but not limited to its transport and security systems, which will be discussed as example in different parts of this chapter.

First, this concept sheds light on the complex organisational effort involved in megaprojects. Often "a special purpose organisation" is created to plan and execute such projects. For example, the 2012 London Olympics created the *Olympic Delivery Authority (ODA)*, which acted as the client for the program, and the *CLM* – the temporary joint venture between CH2M Hill, Laing O'Rourke, and Mace – which was formed specifically to act as the ODA's "delivery partner" (Davies and Mackenzie 2014). This type of organisation facilitates complex cross-institutional collaboration (Sydow and Braun 2018) and governs its semi-detachment link to "permanent" organisations, most notably private or public sponsors and project-based firms (Winch 2014). Thus, the material outputs were intertwined with a complex social and organisational fabric involved in the design, execution, and use of venues, both during and after the Games.

Second, temporary organisations are purposeful: this immense organisational effort exists to attain a deliberate change, in our case, to create a meaningful intervention in an engineering system (Geraldi et al. 2017). For example, the 2012 London Olympics had a purpose that went beyond the delivery of the sport venues and related infrastructure. The project aimed to use the momentum created through the Games "to maximise the economic, social, health and environmental benefits of the Games for the UK, particularly through regeneration and sustainable development in East London' and 'to achieve a sustained improvement in UK sport before, during and after the Games, in both elite performance – particularly in Olympic and Paralympic sports – and grassroots participation" (Pellegrinelli et al. 2011). And indeed, the London Olympics approached its goal. East London has improved significantly, and the Games triggered initiatives, planned and emergent, to incentivise sports and healthier lifestyles that include physical exercise. However, how can one know whether the goals have been actually achieved? What would "regeneration and sustainable development" actually mean, and when would one know it has been "achieved"? These questions indicate that such goals are *wicked problems* (Rittel and Webber 1973) and that it is difficult, if not impossible, to determine exactly what could be done to ensure their realisation or to know whether the problem is "solved", as resolving one part of the problem might lead to unintended consequences elsewhere. Thus, such wicked problems are not easily definable as goals, but rather are approached and negotiated over time. Such problems are not uncommon in the context of engineering systems. As these systems are increasingly complex (Oehmen et al. 2015) and dependent on surrounding systems (de Weck et al. 2011), the intervention created through megaprojects can produce unexpected results. Thus, while the projects are inherently purposeful, their wicked and socio-technical nature resists attempts to develop clear-cut recipes that will allow them to achieve their purpose (Pellegrinelli et al. 2011).

Third, temporary organisations are finite. The temporary organisation works like a firm that has a large turnover equivalent to the project budget and a significant cash flow. However, unlike other organisations, temporary organisations are expected to end (Lundin and Söderholm 1995). Like parenting, projects are the gestation period of a new life, with an expectation that they will lose relevance and even become obsolete. Accordingly, a project goes through a life cycle, usually starting small, involving only the core team. At its peak phase, it coordinates the work of thousands of people, some directly contracted by the project, others through its large supply chain of subcontractors. The project then approaches its end, and its organisational support decreases. As with parenting, if all works well, the children gain independence as they approach adulthood and develop in their own way, to the delight and sometimes despair of their parents. Projects also mature and develop in partly controlled, partly uncontrolled ways, under many influences and with several surprises along the way.

The maturing process does not end at an exact deadline. Turning to our parenting analogy, it is recognised that although turning 18 signalises adulthood in most Western cultures, the role of parents is never quite completed – parents are never ex-parents, and the time of "letting go" is gradual and does not follow a linear plan nor a specific deadline – it depends on the child. Analogously, complex contractual agreements define scope of responsibility and dates of handover; however, the interventions in engineering systems rarely follow such schedules in a strict manner, and the actual process of turning projects from an output to outcomes and benefits is in itself wicked. Accordingly, in the 2000s, project studies and practice realised that the benefit realisation of projects should be considered as part of the project and that such benefits are complex and uncertain, require deliberate management, and can take place years after the project has been officially completed (Atkinson 1999; Breese 2012). Some scholars even suggest program management, with its flexible structure around tranches of work, to be a more appropriate way to manage (complex) projects, which are not terminated, but instead converge to an end (Pellegrinelli et al. 2011).

Thus, looking at megaproject management as a temporary organisation, we choose to embrace its wicked nature as opposed to forcing it to fit a plan-execution methodology. As such, in this study, megaproject management is seen as the deliberate orchestration of a purpose-driven temporary organisation based on socio-technical coordination and collaboration across interacting hardware, software, and knowledge-bases (Tee et al. 2019).

Conceptual Controversies on Megaproject Success

After discussing what constitutes managing projects, this section explores the controversies surrounding the concept of megaproject success. The definition of success is straightforward if projects are understood as a methodology to deliver results according to a predefined plan. In such cases, success means completing the project to plan, usually measured by the iron triangle – meeting predefined time, cost, and scope. According to this definition, examples of "project disasters" abound. For example, the Standish Group's periodic CHAOS report continues to show that around 20% of IT projects fail to deliver the intended benefits within time and budget and that around 50% were significantly challenged (Johnson 2020). Sydney Opera House is a classic example (see box) of a megaproject that was truly unique and very hard to achieve and that was delivered way over budget and with a more than 10-year delay. Yet, given its ambition, perhaps it is the expectation of delivering on time and budget that is the problem (Cicmil et al. 2006).

Box 2 Sydney Opera House Project
The building was budgeted at $seven million; it ended up costing $102 million and was completed 10 years after the planned date. The acoustics of the building have been heavily criticised, partly compromising the purpose of an opera house. Increasing tensions in the process of construction led to, among other things, the architect, Jørn Utzon, leaving Australia, never to come back (sydneyoperahouse.com 2019). Yet, the building became the face of Australia to the world; it attracts around eight million visitors and hosts over 1,800 performances annually (Simes et al. 2013). It is an architectural masterpiece that won the Pritzker Architecture Prize in 2003 and is a UNESCO World Heritage building. While the negative side effects are widely discussed, its potential benefits are less publicised and could only be fully recognised long after the project was completed.

Owing to examples like the Sydney Opera House, the literature differentiates between project and project management success. Project success is considered the success of the final project outcome, e.g., the opera house. Project management success, in contrast, refers to the process of delivering the project (Atkinson 1999). However, a critical engagement with the concepts reveals their inherent limitations.

How can one differentiate between the success of the process and the outcome if the outcome is shaped through the process? For example, allowing more flexibility in the redefinition of project plans and objectives could lead to higher project success, but it will likely lead to project management failure, as such redefinitions often cause delays, rework, and over costs. Accordingly, reviews of the literature also suggest that the notion of success can change over time, extending from implementation of the project over to the entire life cycle of its outcomes (Jugdev and Müller 2005). Accordingly, Shenhar et al. (2001), Morris (2013), and others call for project leaders to be responsible for the business success of the project or its ultimate legacy. However, extending the concept of success is useful but not sufficient to address the conceptual shortcomings of success. First, changing how projects are managed cannot guarantee project success. Project success is inherently uncertain, as it depends on how society will create value out of the project outcomes in the future. Thus, luck may play a defining role in a project's success. Second, megaprojects impact different groups of stakeholders who have different understandings of success. For example, the Itaipu dams have been generally considered to be a success. The Itaipu is a system of dams that cross Paraguay and Brazil that were installed over a period of 10 years. Today, they provide 2.6 billion megawatt hours (MWh) and employ more than 3,000 people; the project promoted progress and development of Latin America and secured a stable and clean source of energy (Itaipu 2020). Yet, the dams can also be considered a disaster for the river ecosystems and the 10,000 families who were living on the bedsides of Parana River, who were neglected during the project process and who became homeless (Pereira 1974). Nearly 40 years after its opening, the region is still plagued with poverty, alcoholism, and other social issues (Lima 2006). The project was also used politically to promote a narrative of the "Brazilian golden years" under its then dictatorship regime. Itaipu dams can therefore be considered a success to some and a disaster to others. Thus, success is subjective.

Indeed, as success criteria moved from meeting the requirements of the iron triangle in the 1960s to 1980s to more inclusive measurements, including stakeholder satisfaction and strategic benefit realisation (Jugdev and Müller 2005), there has also been an ontological shift toward a symbolic and socially constructed facet of success (Ika 2009). For example, Kreiner (2014) empirically demonstrates the relevance of socially constructed notion of project success using a case study that fails in terms of the iron triangle, but which is considered a huge success, as core project stakeholders were able to create and sustain a shared feeling of success. Note that the development of such a shared feeling is intertwined with a project's results. Kreiner's main contribution is not that the iron triangle is inherently wrong, but that the challenge in achieving project success lies in the shared feeling of success, which might, but does not have to, involve meeting the iron triangle.

Overall, the concept of megaproject success is ambiguous and highly disputed; different versions of success and failures can be constructed alongside the project and coexist. In such a context, the meeting of predefined criteria is neither enough nor required for success, whereas developing a narrative of success becomes central.

Having that in mind, the next section will explore four core challenges involved in managing megaprojects successfully.

Challenge 1: Delivering Purposeful Interventions

The challenge: in order to deliver purposeful interventions, megaproject management needs to balance plans and adaptability (Wied et al. 2020a). The plans and the estimations are important – they ground the decision for people and organisations to get involved with a specific project over other potential investments (Flyvbjerg 2014). Plans and estimations are usually perceived as public promises, and it is expected they will be followed. They also facilitate communication, legitimise actions, and, in some contexts, are legally required in order to carry out the work. However, while plans may guide the work, they will never represent what will happen (Maylor 2001). As the project unfolds, people's intentions and interests will mature (Kreiner 2014). Contextual changes might also impact the project and, in some cases, even render the project irrelevant, if it is not adapted. As engineering systems are complex, a megaproject will have several interfaces and interactions with other parts of the system, and it is very difficult to foresee all the interfaces; close coordination and adaptation is required to make "ends meet" (Geraldi 2008). Finally, initial ideas and concepts may not work as planned, and the challenges involved in undertaking the megaproject might be underestimated, for good or bad (Ika 2018). The consequence is that project practitioners perceive deviations from the plan as both something to be avoided and something that is unavoidable and sometimes even essential to keep the project relevant. Thus, one of the core challenges of megaprojects is to deliver purposeful interventions that balance the need for plans and structures on the one hand and adaptability and flexibility on the other.

Management approaches: There is no agreement in the literature about the balance between plan and adaptability. One line of work emphasises the ability to plan ahead, anticipate changes, and predict future scenarios accurately. The main premise is that it is possible and advisable to plan for the future in the very beginning of projects, the so-called project front-end, and that such plans can be realistic. At the front-end, managers will set the strategic direction of projects, establish relevant relationships, set expectations, and gain the commitment of core stakeholders. Morris (1994) argues that the seeds of success and failure of projects are sewn with the management of this front-end. Yet, despite overall agreement of its relevance, project practice still overlooks the front-end of projects and assigns project managers far later in the project process, when the first plans have been already made and endorsed (Morris 2013). In such constellation, the project manager is put in a difficult situation, being responsible for the delivery of the (often unrealistic) promises of others (Pinto 2000). Morris calls for the involvement of project managers upfront, which would allow them to help develop more realistic plans that include the expertise of the project manager, who has likely delivered projects in the past and who will become responsible for the delivery of the plan.

Flyvbjerg agrees with Morris about the relevance of the project front-end and the possibility of realistic planning and the need for strategic thinking and due diligence. However, unlike Morris, who identified issues in the management and organisational approaches of projects, Flyvbjerg (2014) is intrigued by the sustained optimism in megaproject estimations. He argues that if project cost and budget are difficult to estimate, project costs would sometimes be underestimated and sometimes also overestimated. Yet, most project plans are overly optimistic rather than overly pessimistic. Based on this observation, he suggests that the underestimation of costs and duration and the overestimation of project benefits is caused by either delusion, that is, a cognitive error, or deception, that is, the strategic use of underestimation to get projects approved (Flyvbjerg et al. 2009). He calls this observation *strategic misrepresentation* and suggests a technique called *reference class forecast* to curb optimism and derive realistic plans. The technique is based on comparisons of the project estimations between similar projects, for example, airports of similar sizes. The concept has received wide attention in academia and practice, yet has several limitations that will be discussed in the next paragraphs.

The other line of work favours creativity and flexibility over plans and reliability. It recognises the uncertainties in projects and focuses on making the project right at the end, not at the outset. It recognises that core project stakeholders' interests and intensions change across the life cycle of the projects and the project objectives will evolve accordingly (Kreiner 1995), as most people will have difficulties truly knowing what they want before experiencing it (Weick 1995). As Hirschman's concept of the "hiding hand" suggests, ignorance of future project challenges is fortunate (Hirschman 1967). Were project stakeholders to know the difficulties involved with achieving the shelf structures of the Sydney Opera House, they might have not approved the design, resulting in lost advances in structural engineering that were made by the project, as well as the creation of an iconic symbol of Australia. Hirschman argues that just as the unknown future brings challenges, it also activates mankind's creativity and ingenuity to overcome barriers and make the project work in the end; this ingenuity is what propels projects forward and allows people to solve barriers on the way.

One could argue that such projects would fail in a cost-benefit analysis and that the resources used in the project could be "better invested" in different projects. Yet, such arguments fail to consider the potential long-term benefits of the projects that go beyond financial measures and encompass hard-to-measure, yet not less relevant, aims, such as promoting human rights, adapting to climate change, improving social development and governance, and reforming the public sector, among others. As Ika (2018) argues, when taking a longer-term view on projects, Hirschman's ideas have been supported through the analysis of multiple cases, both qualitatively and quantitatively, favouring the understanding of the micro in megaprojects, that is, the actual challenges of the projects as opposed to abstract and detached estimations and deviations from plans (Ika 2018). This line of though does not argue though that we should just start daring projects, with no strategic consideration, and things will just sort themselves out of the way, nor that adaptability and learning will necessarily lead to long-term success. Instead, it argues that daring projects are less likely to meet initial expectations, and the implication should not be to not having these projects, but instead to reconsider the evaluation of success.

Moreover, this line of work promotes different project practices on the ground, emphasising the need for learning, experimentation, and adaptation – not unlike practices promoted by design thinking. Such forms of managing projects existed from the very beginning of project management, as early as the 1940s in projects like the Manhattan Project; yet project practices have primarily emphasised planning over adaptability (Lenfle and Loch 2010). The pendulum is currently swinging back to more adaptive forms of managing and perhaps even planning for emergence, both in practice, as observed in movements like Agile (Beck et al. 2001), and in academia, with movements such as Scandinavian project management (Packendorff 1995) and rethinking project management (Winter et al. 2006). Today, the concept of resilience is gaining momentum. For example, Wied et al. (2020b)'s comprehensive literature review identifies over 200 definitions of resilience and proposes a multi-dimensional morphology of the concept, pointing to the varying nature of changes impacting projects and their consequences. In a following paper, Wied et al. (2020a) then explore generalisable practices to enhance project resilience throughout its life cycle. Overall, there is growing recognition that megaprojects are inherently uncertain and ambitious and that they are worth doing not for financial reasons, but because they have the potential to propel humanity forward. Plans are relevant for coordinating and legitimising work and supporting decisions and actions, but it is naïve and unhelpful to expect the project to strictly follow the plans; instead of a plan, megaprojects demand planning (Dvir and Lechler 2004).

Challenge 2: Integrating Complex Work Under High Levels of Uncertainty

Challenge: Megaprojects are inherently complex, that is, they comprise a high volume and a high variety of interrelated elements (Geraldi et al. 2011). For example, a megaproject like the construction program of the London Olympics, as noted by Davies and Mackenzie (2014, p. 778), "consisted of over 70 individual projects (planned, approved and managed by principal contractors) including 14 temporary and permanent buildings, 20 km of roads, 26 bridges 13 km of tunnels, 80 ha of parkland and new utilities infrastructure". These different projects interface with one another, so that small changes can have cascading effects across the megaproject (Williams 2005). A core task of megaproject management is to coordinate the work, in light of its complexity and the inevitably turbulent conditions, where plans change, requiring behaviour changes of the people in and around projects (Geraldi et al. 2017). How can such mega endeavours be organised?

Management approaches: The management of such systems requires integration capabilities (Davies et al. 2009) and organisational settings that are particular to megaprojects and which follow the core principles and ideas of systems thinking (decomposition, black boxes, and interfaces). While Brandenburg Airport exemplifies how not to do it (Geraldi and Stingl 2016), London Terminal 5 developed innovative management and contractual practices that benefitted its development (Davies et al. 2009). The contrasting examples suggest that although "one size does not fit all", some approaches are better than others.

Box 3 Berlin Brandenburg Airport

The Berlin Brandenburg Airport project has been a constant source of outrage since its originally scheduled opening in 2011. Public media argue that the project suffered from overly ambitious plans, a lack of coordination, and constant scope change. The contractual setup was also not helpful for responding to changes. Instead of a consortium involving main project partners that is managed by project consultants with experience in the technical and commercial interfaces of such a complex project, the project owner decided to manage the contracts themselves, despite their limited experience with such projects. Interfaces between contractors became hard to manage, and problems were exacerbated when the airport company initiated major changes at late stages in the project, sometimes driven by political interests. Subcontractors could no longer keep up with the cascading effects generated by such constant changes, and some even asked for a temporary suspension of construction work, which was denied (Geraldi and Stingl 2016). The constant changes and lack of coordination between contractors led to over 2,000 issues in the fire protection systems, which stopped several attempts to open the airport. At the time of writing, the airport is due to open on October 31, 2020, 9 years later than planned (Schuetze 2020), and the projected costs have tripled to approximately 6.6b EUR (Tagesspiegel 2020). The airport's financial situation has worsened following the COVID-19 pandemic, exposing the airport to an even higher risk of bankruptcy (Gemünden et al. 2020).

It goes beyond the scope of this chapter to provide a comprehensive overview of all useful managerial practices developed for megaprojects to address their complexity and means for improving coordination of megaprojects. We have chosen instead to focus on three practices and engage with them in more depth: coordination through integration capabilities, coordination through timing, and coordination through roles. The first is the concept of the systems integrator and its integration capability. The systems integrator "must establish the project governance structure, assume responsibility for risk, work with partners in integrated project teams, and lead a transient network of external suppliers consisting of dozens of first-tier suppliers, hundreds of contractors, and thousands of subcontractors" (Davies et al. 2009, p. 102). Davies and colleagues examined the systems integrator roles across megaprojects in the UK, including the London Olympics and Heathrow Terminal 5, and one of the main conclusions of the work is that "systems integrators seek to improve megaproject performance by learning to implement innovations based on the 'recombination' and 'replication' of a system of production processes" (Davies et al. 2009, p. 102). The execution of a megaproject requires six processes related to integration:

- Systems integration to coordinate the design, engineering, integration, and delivery of a fully functioning operational system (Sayles and Chandler 1971; Sapolsky 1972)
- Project and program management to support an integrated supply chain
- Digital design technologies to support design, construction, integration, and maintenance activities
- Off-site fabrication, pre-assembly, and modular production, to improve productivity, predictability, and health and safety
- Just-in-time logistics to coordinate the supply of materials, to increase speed and efficiency
- Operational integration to undertake systems tests, trials, and preparation for handover to operations (Davies et al. 2009, p. 102)

Box 4 Heathrow Terminal 5
Heathrow Terminal 5 (T5) is a large and complex extension of the Heathrow Airport, which involves adding a new terminal to the airport, expanding its current capacity of 67 million passengers a year to 95 million a year. The project includes a metro line and road extensions, construction of the new terminal, and innovations in airport logistics. In terms of project management, the project's main innovation is the "T5 agreement", where BAA (British Airport Authorities) holds all the risks associated with the project, rather than transferring the risks to external suppliers. Comprising 16 major projects and 147 sub-projects, employing up to 60,000 people, the project is considered a classic example of a "megaproject" not only because of its size and high cost but also its transformative impact on the UK construction industry (Case vignette based on Brady et al. 2006; Hammond et al. 2008).

The nature of the tasks and their level of sophistication highlight the complexities involved in the execution of megaprojects, including the temporary coordination of thousands of people across many organisational boundaries. While Davies et al. emphasise organisational solutions for this mega coordination task, another body of work looks at the role of time and timing as a coordination mechanism, which is the second form of coordination discussed here. For example, Lindkvist et al. (1998) contrast classic sequential development of projects with a fountain model, which draws on concurrency. Dille and Söderlund (2011) explore the temporal work of project actors to negotiate time horizons, deadlines, and the overall project rhythm. Not only does time help to coordinate the work, it is also disputed across project partners, each wishing to impose the time and timing that would be most suitable to their own operations. Dille and Söderlund called this temporal practice of aligning time across project partners *isochronism*, alluding to the institutional phenomenon of *isomorphism*, where organisations copy each other's structures to gain legitimacy. Following a similar line of work, Svejvig et al. (2019) discuss time and speed as a value, that is, something that is not necessarily a benefit for project stakeholders. Stjerne et al. (2019) also explore temporal boundaries as forms of coordination in inter-organisational projects. Thus, time and temporality constitute not only a characteristic of projects but also a form of coordination of work.

The third practice relates to roles and positions. Roles and positions represent relevant, yet often overlooked, means of coordinating work in the project. Organisations involved in megaprojects exploit repetition and stability in roles (Bechky 2006) and processes (Davies et al. 2009). Bechky (2006) was the first to identify the relevance of roles in project coordination. She was intrigued by the speed at which film settings started to work harmoniously together. She identified that in film settings (like in several other project-based professions), role expectations were institutionalised across the sector and enacted in situ. Yet, these very roles and processes are also the subject of conflict and negotiation due to the highly political nature of megaprojects. Van Marrewijk et al. (2016), writing about the Panama Canal, illustrate this balancing act very well, as they describe how political role negotiations are balanced with social harmony-seeking practices. These balancing acts are dynamic and evolve throughout the project.

Coordination of project work is complex; it crosses organisational boundaries and requires careful and skilful integration that balances the need for economy of repetition with contextual sensitivity to adapt to the realities of each megaproject and its needs.

Challenge 3: Collaborating with Friends and Foes

Challenge: Managing project stakeholders and developing shared narratives is remarkably hard. Megaprojects are highly political and involve a large number and heterogeneous stakeholder groups that hold different and sometimes contradicting views (Tsai et al. 2008). In addition, both the stakeholders and their views can change as the project develops (Tryggestad et al. 2013). The literature in the area is comprehensive and diverse. We have chosen to treat here two areas of research, one that is very established and common practice in projects – stakeholder management – and the other that is emerging – the dark side of projects.

Management approaches: Project stakeholder management is considered a core area of practice and research in megaprojects. Based on the classic work of Friedman and Miles (2010), project scholars and practitioners have developed a toolbox for stakeholder management that is based on established processes to identify, assess, and manage stakeholders throughout the project. One of the classic mistakes in the employment of the toolbox is to reduce stakeholder management simply to the use of the tools. The tools will not manage the stakeholders, but tactful conversations and savvy negotiations will.

Project managers are challenged to maintain good relationships and collaboration across the project life cycle. The diversity of the stakeholder landscape is particularly salient in megaprojects. Their interventions in engineering systems are of such a magnitude that they are subject to media coverage and public scrutiny. Accordingly, there is a growing opposition from "the public" to megaprojects. While public participation makes the project development process more democratic and potentially making the projects more valuable and useful, public participation can attenuate the difficulties in managing projects (Scott et al. 2011) and may raise issues of governance (Pitsis et al. 2014) and governmentality (Clegg et al. 2002). Moreover, new and sometimes unexpected stakeholders can emerge, and their influence on the project might change, as Tryggestad et al. (2013) illustrate. Looking at a large real-estate development project from an ANT perspective, Tryggestad et al. describe how an endangered species of frogs turned from a disturbance to an asset. The authors decoupled the terms "stake" and "holders" and suggested a dynamic view on how non-human stakeholders can become a matter of concern for the project. Such a dynamic and attentive view of emerging stakeholders is therefore important in megaprojects.

In an attempt to shed light on these more complex human intricacies, the literature surrounding stakeholders and project actors in megaprojects has moved away from a focus on tools and processes to one that explores the understanding of human behaviour in and around projects, drawing on, among other things, practice theory (Cicmil et al. 2006), political science (Clegg and Courpasson 2004), and psychology (Stingl and Geraldi 2017).

In line with this development, recent literature has also started to explore the dark side of megaprojects. The dark side refers to illegal and/or unethical practices, such as modern slavery, corruption, money laundering, unsustainable exploitation of natural resources, illegal disposal of waste, and other uncomfortable topics (Locatelli et al. 2019). For example, slavery is still a *modern* problem and is shockingly high: the UK Home Office estimates that the number of victims and survivors of modern slavery in the UK (GOV.UK 2019) is 13,000 and rising rapidly (IMGMS 2018). The phenomenon is so relevant and timely that the UK "Modern Slavery Act" dates back to 2015. Globally speaking, there are over 40 million modern slaves, including about 25 million in forced labour. A consistent number of these modern slaves are used in project-based industries like construction. In the USA, "unskilled migrants, predominantly from Mexico and Central America, account for approximately 25 per cent of the construction workforce. Undocumented and largely working without union representation, they are highly vulnerable to exploitation" (CIOB 2015). Similarly, projects are subject to other dark practices, such as corruption (Locatelli et al. 2017) and exploitation of people (Hesmondhalgh and Baker 2013). The dark practices are important to megaprojects. They can be uncomfortable and worrying to project practitioners and represent important behaviours and dynamics in and around projects and hence are an important consideration for understanding how megaprojects are actually managed. Yet, research in the area is still in its infancy, and there are active calls for further development.

In conclusion, there are limits to taking a "technocratic approach" to megaprojects, that is, a focus on merely rational and instrumental management. Megaprojects exist to bring about change while respecting stakeholders and winning the hearts and minds of people in and around the project – or at least enough of them.

Challenge 4: Innovating and Learning Under Tight Time and Budget Constraints

Challenge: Because megaprojects are considered to be unique, novel, and uncertain, processes for reducing uncertainty have been widely used during the design and execution of many megaprojects, with some people even arguing that risk management is project management (Loch et al. 2006). Such contexts are therefore not seen to be attractive settings for innovation and learning, which increase, rather than reduce, uncertainty. Moreover, learning from a unique endeavour is difficult to capture and use to improve the performance of another one-off project (Prencipe and Tell 2001).

Under the traditional project management model still commonly used, megaprojects have failed to achieve their original objectives because clients believed they could identify all of the uncertainties that might impact on the project at the start, freeze the design at an early stage, and use fixed-price contracts to transfer the risks during the execution of the project (Davies et al. 2017). Because megaprojects are so uncertain, clients traditionally prefer to rely on existing routines, tried and tested practices and proven technologies rather than introduce what they traditionally perceive to be additional risks associated with innovation (van Marrewijk et al. 2008). This is surprising because many years ago, Hirschman (1967) introduced the idea of the "hiding hand" to identify the creativity (see above) and innovation that is unleashed to address uncertainties not foreseen at the start encountered during the execution of large-scale projects, particularly those with long gestation periods. An invisible hand hides the difficulties from us to help get projects started, and innovative resources are creatively employed to solve unanticipated problems when projects are underway. The hiding hand has been criticsed for being overly optimistic about the downstream innovative capacity of megaprojects to solve problems overlooked by upstream planners (Flyvbjerg 2014). Yet the mechanism does recognise the potential for applying innovation to resolve unforeseen uncertainties and complete megaprojects more efficiently (Davies 2017).

Megaprojects are under pressure to deliver work within the constraints of time and budget. Project practitioners are therefore challenged to find economies of repetition (Davies and Brady 2000) to increase its effectiveness without compromising on the need for innovative thinking and learning. Innovation in megaprojects depends on learning from previous projects, identifying successful practices and applying them – often in new combinations – on current and future projects. While the outcome of a megaproject is unique, processes, routines, and practices can be standardised, replicated, and repeated to improve performance (Davies et al. 2009). Modularised organisational and technical solutions also assist increased effectiveness through reuse of prior work or routines in different combinations (Thuesen and Hvam 2011). Research in other industries has shown how performance can be improved by moving progressively from one-off, unique to higher-volume automated stages of production (Wheelwright and Clark 1992). It is often assumed that this logic of efficiency improvements is not applicable to megaprojects because outcomes must be customised to each client's requirements and organisations are unable to transfer lessons from one project to the next. However, in a study of the highly innovative Heathrow Terminal 5 project, Davies et al. (2009) found that the volume, frequency, and predictability of tasks performed by a megaproject can be simplified, standardised, and repeated on a large-scale basis. They argue that most megaprojects contain standardised and customised elements. Highly customised practices and technologies developed for megaprojects in other industries (e.g., oil and gas) and standardised processes developed for high-volume production, such as just-in-time logistics, can be adapted and applied to the requirements of each megaproject. Merrow (2011) provides a good illustration of the value of benchmark studies within a specific industry. Merrow's empirical work was based on a large database of oil and gas projects privately held by an International Project Audit firm. This database allows reliable estimations of schedule, budget, and expected return on investment for comparable projects in this industry.

Management approaches: Over the past two decades or so, sponsors and clients presiding over megaprojects recognise that megaprojects often fail because they were unable to innovate, learn, and adapt plans to deal with changing and unexpected conditions (Winch and Leiringer 2016; Winch and Cha 2020). While many new approaches have been developed around the world, research based on new ways of delivering megaprojects in the UK has shown how clients have begun to question the traditional approach and developed new ways of supporting innovation and learning in megaprojects (Davies et al. 2019; Denicol et al. n.d.).

An in-depth study of Heathrow Terminal 5 (T5) showed how client organisations may develop dynamic capabilities – in the case of T5 this was a contractual and collaborative approach embodied in the so-called T5 Agreement – in three phases: learning, codifying, and mobilising to deal with the stability and innovative change in megaprojects (Davies et al. 2016). Action research with Crossrail, another large UK megaproject, presents a four-window approach showing how an innovation strategy was implemented to complete the project more efficiently and effectively (Davies et al. 2014). The authors worked in a collaborative team with members of the Crossrail project to develop a systematic approach to innovation. Davies and Brady (2016) call for ambidexterity in megaprojects, that is, the balancing between exploitation of knowledge through, e.g., the recombination and replication of processes and exploration of new and innovative practices (Brady and Davies 2004).

The work by Davies and colleagues is summarised in an article on how leaders of a number of London's megaprojects developed five simple rules for using innovation to help managers manage megaprojects more effectively: assess what has worked before; organise for the unforeseen; rehearse first; calibrate and apportion risks appropriately; and harness innovation from start to finish (Davies et al. 2017).

The UK case is interesting because it shows how learning occurs and that innovative capabilities are developed beyond the confines of each individual megaproject. Learning and innovation is possible because the enduring relationships and trust established among participants working on previous megaprojects provides a repository of shared learning and prior experience, which can be retrieved when participants work together in the future. Building on Grabher's (2001) research, Davies et al. (2017) suggest that the expanding number of individuals, teams, contractors, and clients working on megaprojects and circulating between them has helped to establish London's thriving "megaproject ecology" and worldwide reputation for the development of innovative new project delivery models. Lessons for the development of such a fruitful context for megaprojects are relevant for the development of functioning engineering systems. Engineering systems build on the orchestration of not one but several megaprojects and benefit from learning and innovation that moves from project to project. The UK case shows that such learning is possible.

Conclusion

Megaprojects are a commonly used vehicle for creating interventions in engineering systems. Despite the best of intentions, directing and delivering a successful megaproject is remarkably hard. In this chapter, we summarised four core challenges and some of its related coping practices commonly discussed in the literature dedicated to managing megaprojects: (1) delivering purposeful interventions, (2) integrating complex work under high levels of uncertainty, (3) collaborating with friends and foes, and (4) innovating and learning under high time and budget constraints. The challenges are not new, but they are still current and relevant, and more research is required to address the challenges associated with megaprojects and their impact on engineering systems. As Hirschman and Lindblom (1962) observed many years ago, large engineering systems require interventions because it impossible to foresee at the outset the incompleteness; newly emerging difficulties and unanticipated opportunities emerge, become visible, and have to be addressed only after the systems became operational for some time.

As an outlook, we suggest four streams of research for managing the dynamics of megaproject engineering systems: First, rethinking the purpose and success of megaprojects is core to the development of the field, of engineering systems, and of society. Following Morris (2013), we call for a stronger ethical commitment of project stakeholders. Such ethical considerations are of particular relevance from the point of view of the engineering systems, as they enable a conversation about what kind of engineering systems the society is willing to invest in. In this regard, scholars can also examine the "dark side of projects", that is, the malpractices in projects and those created through projects (Locatelli et al. 2019). On the bright side, global goals like the United Nations Sustainable Developmental Goals should be a concern for both practitioners and scholars. Coming from this vantage point, future studies can problematise the notion of megaproject success and explore why we do projects and what projects we, each of us, would like to contribute to, and hence, what kind of society (and engineering systems) we will be thereby constructing (Fough Jensen et al. 2016). Such value-driven discussion could also embrace the wicked nature of megaproject intervention in engineering systems, preparing society for a commitment to a certain direction, which can be approached but never reached (Davies 2017).

Second, a promising line of study is to inquire into integration not only within but also across megaprojects. Studies on the institutional context of projects would be welcomed and could potentially pave the way toward innovation in megaproject, as the UK case seems to suggest (see section "Challenge 4: Innovating and Learning Under Tight Time and Budget Constraints"). Such line of research could have potential not only to contribute to practice but also to the growing field of institutional entrepreneurship and innovation (e.g., Battilana et al. 2009; Hinings et al. 2018). Megaprojects would be a case for actors' impact on institutions. Moreover, a macro (systems of systems) perspective on collaboration between partners and contractors is also relevant. In practice, there is a tendency toward the insourcing of project capabilities on the client side. As the case of Brandenburg Airport suggests, integration between contractual partners is not trivial, and the political setting around the project can also slow decision-making processes and create potential conflicts in the projects, with devastating implications for projects if they are not accompanied with development of relevant capabilities (Winch and Cha 2020). The tendency for stronger governance between megaprojects and increased sponsor capabilities is particularly beneficial from the engineering systems perspective, as it allows megaprojects to be considered as a portfolio of interventions. In this way, megaprojects encourage learning not only about the processes of managing but also about interfaces between various socio-technical systems, which are particularly intertwined in modern engineering systems (de Weck et al. 2011).

Third, innovation and learning continue to be a core arena of studies in megaprojects. Studies such as those by Davies et al. (2018) are a good starting point and propose valuable research avenues connecting innovation and projects. From a more critical view, the concept of innovation could also be problematised. From a Schumpeterian perspective, innovation is not only about creativity but also about destruction, as the new and innovative proposes new avenues that may destruct current industries and practices. If so, what would we like to destruct in megaprojects in order to create space for the new to emerge? This logic could also extend to the design of engineering systems through megaprojects: What would we like megaprojects to destroy in engineering systems and what could emerge in their place? Such discussions could provide fruitful terrain for further developments in practice and academia.

Fourth, megaprojects and engineering systems are intertwined. Megaprojects are fundamental for the shaping of engineering systems, and engineering systems dynamics are essential for the management of megaprojects and for understanding the very existence and need for the megaproject in the first place. Going forward, we envisage even stronger interconnections in research and practice.

Cross-References

► Choosing Effective Means: Awareness of Bias in the Selection of Methods and Tools
► Engineering Systems Design Goals and Stakeholder Needs
► Engineering Systems Interventions in Practice: Cases from Healthcare and Transport

▶ Ethics and Equity-Centred Perspectives in Engineering Systems Design
▶ History of Engineering Systems Design Research and Practice
▶ Public Policy and Engineering Systems Synergy
▶ Risk, Uncertainty, and Ignorance in Engineering Systems Design
▶ The Evolution of Complex Engineering Systems
▶ Transitioning to Sustainable Engineering Systems

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Asking Effective Questions: Awareness of Bias in Designerly Thinking

26

Rebecca Anne Price and Peter Lloyd

Contents

Abstract

The formulation of questions in processes of design is an activity affected by cognitive biases inherent to humans. Cognitive biases, developed through gaining experience, influence how decisions are made during problem solving. When an outcome is predictable, experience provides mental shortcuts or heuristics to enable the problem solver to act effectively. When an outcome is uncertain, cognitive biases can wrongfully project preconceptions, elevate self-interest, and undermine the problem solver's greater ambitions for positive impact. Mitigating cognitive bias is thus vital for design problem solving under conditions of uncertainty. Designers explore uncertainty through an approach typified by human empathy, problem framing, and creativity. This chapter reveals the nature of asking effective questions within designerly thinking. This means understanding nuances of context, surfacing novel insights about how a system performs, and crucially working out how people within systems experience the world around them.

R. A. Price (✉) · P. Lloyd
Department of Design, Organisation and Strategy, Faculty of Industrial Design Engineering, Delft University of Technology, Delft, The Netherlands
e-mail: r.a.price@tudelft.nl; p.a.lloyd@tudelft.nl

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Keywords

Bias · Complex systems · Designerly thinking · Effective questions · Engineering systems · Engineering systems design · Problem-solution co-evolution

Introduction

Asking effective questions allows engineering system designers to uncover constraints and clarify the nature of parameters, probing for deeper human insights from actors within systems. Asking effective questions allows the curious mind to learn about the environment around them – the environment which they have tasked themselves to improve. Yet the formulation of questions asked is often affected by cognitive biases and preconceptions. These preconceptions are inherent to human knowledge. Based on lived experiences, cultural frameworks, and beliefs, people grow and learn accepted ways of behaving and communicating. These experiences provide heuristics for decision-making when the outcome is likely or predictable.

However, when the outcome is uncertain, these biases can influence judgments and undermine the problem solver's greater ambitions for positive impact. Lloyd and Scott (1994) showed how, as engineering system designers develop expertise, they also move from a "first principles" approach to design, one where the best-fit solution is the starting point, a more efficient way to design, but one that may bring unquestioned assumptions. In the design of complex systems, for example, improving the effectiveness of a public health system, a problem begins in an ill-defined state, "we are not sure where to begin, let alone a next step," the system designer might ask themselves. What usually follows is an exploration through uncertainty where the designerly thinker confronts their own preconceptions about how best to improve the environment around them. It is the ability to be aware of, and reflexive to, these known preconceptions that offers designerly thinkers an ability to detach from the current situation and question *what can be*.

This chapter will clarify the nature of designerly thinking and explain why engineers must embrace the approach in light of the systemic nature of engineering problems encountered. We touch on the social requirements for engineers designing for complex engineering systems. New challenges to practice regarding negotiating individual and collective biases are presented and discussed in lieu of the central theme of this chapter, the awareness of biases. The chapter closes with a summary and points to future research pathways.

Technical Problems, System Problems

Popular rhetoric holds that design and engineering use distinctive methodological pathways and principles to progress from problem to solution. The engineer investigates and defines utility functions and subsequent parameters and then undertakes a process of optimisation. The designer explores through an approach typified by human empathy, problem framing, and creativity. A closer look at the motivations of the two fields reveals clear similarities. Designers attempt to solve problems in the best possible way. Engineers seek to arrive at optimal solutions. Designers can learn much from how engineers undertake optimisation. Engineers can learn from designers too, particularly how to work with ill-defined problems. Exploring synergies between these traditionally distinct disciplines is a valuable activity given the hybrid specialisations of systems engineer and systems designer.

How a problem is framed greatly informs the pathway to a solution. Jakobsen and Bucciarelli (2007) illustrate this with two examples shown in Figs. 1 and 2. In Fig. 1 a mechanical problem is shown, and with Fig. 2 this problem is reframed to introduce the wider societal context. These two examples are pertinent in this chapter in relation to the way problems are framed and the subsequent inquiry of the problem solver. The first example is a mechanical problem calling the engineer to calculate the force required to move a wheel (lawn roller) over an uneven surface. The problem is presented mathematically, using trigonometry and statics. Aside from the lawn roller reference, the wider context of this problem is excluded. Thus, questions such as the following are not relevant to the problem frame and subsequent solution pairing: *Whom or what will pull the wheel? What are the consequences of "bumps" to the quality of the lawn roller or any load being carried?* In this problem frame, there is one correlating solution to identify, *F (force)*. The engineer's

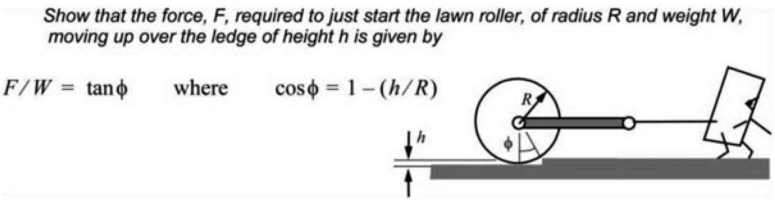

Fig. 1 Mechanics problem reduced to essential forces (Jakobsen and Bucciarelli 2007)

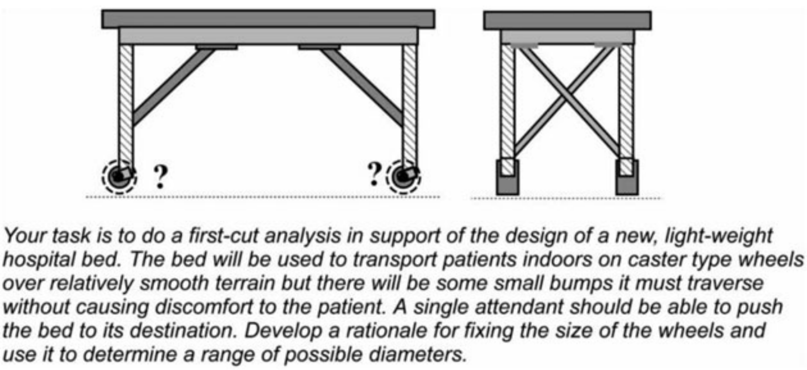

Fig. 2 Mechanics problem transformed to incorporate context: hospital bed wheel size (Jakobsen and Bucciarelli 2007)

heuristics kick into gear with the process of calculating force guided by a discernible pathway between theory and practice. Learnt heuristics provide effective reference points for judgment and decision-making in this controlled environment.

In Fig. 2, the mechanical problem set by Jakobsen and Bucciarelli (2007) is reframed. The problem now concerns designing a patient trolley for a hospital context. Question marks hover over the wheels of the trolley – calling upon the engineering student to focus attention *here*. Jakobsen and Bucciarelli (2007, p. 296) write:

> The first (disturbing) feature of the problem statement is the lack of information which might enable students to begin, none the less solve, the exercise. This is intentional. The student is meant to grapple with the question: What additional information do I need to respond? And a related question: Where might I obtain this needed information? What information is irrelevant?

The engineer must now undertake a process to establish the utility of the trolley. The context of the hospital will be mapped: *How high are the "bumps"? How wide are corridors and lifts? What is the friction co-efficient of various surfaces in the hospital in relation to possible wheel materials?* Once the parameters are identified, an optimisation process can begin. Yet in such a social-technical context, this approach also carries risk.

What is often overlooked in efforts to establish the parameters and begin a process of optimisation is exploration beyond essential utilities to the extended needs of users in the hospital system. Consider the effect of these *projection and egocentric biases* (Tversky and Kahneman 1974) on the project if left untreated:

- All patients and hospital staff are similar; they have similar experiences and needs.
- All hospitals are similar; they have similar layouts, conventions, and regulations.

The assumption that most hospitals are similar is relevant. Hospitals are governed by strict regulations and building codes to ensure safety. Certain wards, such as intensive care, emergency, neonatal, or oncology (and so on), will require unique equipment and processes of care. The hospital bed will come into contact with the various environments such as operating theatres or radiology. An engineer will ask: *What are the nuances of these environments and how will this influence the design of the hospital bed?* A designerly thinker considering the broader system might ask: *How might I undertake this project in an instrumental way to improve the hospital for the many different people who visit it?*

Many patients are also similar. They have illnesses or injuries and require treatment and care. They require a hospital trolley that supports their weight and any related equipment. Hospital staff by virtue of their occupation have similarities too. Yet in both cases, patients, doctors, nurses, technicians, training staff, family, cleaners, and many more stakeholders will interact with a hospital trolley in various and sometimes unexpected ways. Their experiences will be greatly informed by the mobility (and stability) of the hospital trolley. Consider how a patient is rushed around corridors and through tight doorways to an operating theatre by doctors and nurses, as their condition becomes critical. The manoeuvrability of the trolley is crucial. Consider how the child being wheeled to X-ray with a fractured leg feels every "bump" in the floor through their broken bone. The smooth ride is part of treatment and recovery. These experiences can be bettered through thoughtful *designerly systems engineering*.

Beyond the needs of users, the systems engineer will be tasked with resolving how the design of a hospital trolley interacts with the broader health system. The unit of the individual trolley is one small part within the health system. Yet an incremental improvement to the wheel design of a hospital trolley can be harnessed as an instrumental intervention with consequences across the wider health system. With improved trolleys, the designerly systems engineer might now ask: *How can increased patient mobility create capacity within a crowded health system? How might the trolley reduce complaints or associated costs of poor patient transport? How might those saved expenses now be reinvested to improve infrastructure or training? How might implementation of the trolley reveal the extent of doctor/nurses shortages?* These questions transform a simple mechanical improvement into a conduit for driving systemic reform. This can be reinforced when the benefits of a new design form the basis for new regulations. The widespread adoption of a superior hospital trolley across a healthcare system thus facilitates an accumulation of improvements. A strong measure of a country's socio-economic status is the quality of its healthcare system, and innovation is a reflection of a dynamic and self-improving system. Just as a wheel redesign can be instrumental within one hospital, one hospital undertaking innovation to explore *what can be* becomes instrumental across the greater healthcare sector. Only when effective questions are asked and the designerly systems engineer mandates themselves with this greater task are such transformations possible.

When working with ill-defined problems, such as the hospital trolley in Fig. 2, exploration must precede optimisation. An optimisation process that is later disrupted by new insights, utility functions, and parameters will require costly backtracking. Discipline and patience is required to defer first ideas and undertake an investigation into the context of the hospital. In Fig. 1, the assumption was that the provider of the force was inexhaustible. In Fig. 2, the engineer must now confront the various types of loads and subsequent forces – physical and social – required to move the trolley.

Consider the physical, cognitive, and emotional condition of a nurse after a 12-hour shift and how intuitive use of the hospital trolley becomes paramount. Deeply considering the human condition at the end of 12-hour shift requires the engineer to activate empathy – to be designerly. Heylighen and Dong (2019) cite the seminal research of Pat Moore who transformed herself into an 85-year-old woman in order to understand the everyday life of elderly women in the absence of wealth (Moore and Conn 1985). While the designerly systems engineer might not undertake the same transformation, the essence of *walking in someone's shoes* to understand phenomena provides a research approach that can be actioned through design methods such as journey mapping, scenarios, role-playing,and storytelling (Price and Wrigley 2016; Price et al. 2018).

The designerly systems engineer might now ask, *how many shoes must I walk in?* While it is inefficient to comprehensively identify and map the needs of all stakeholders, it is important to explore the context and empathise with people within a given system in order to develop principles and frameworks that initiative iterative prototyping. Expert designerly thinkers will sense *intuitively* an exhaustiveness to their exploration (Dorst 2017). All of the most essential utilities and needs of stakeholders are mapped. The mundane and surprising scenarios of use are anticipated. One feels ready to begin generating ideas. The phrase *paralysis by analysis* is pertinent here. Peter Lloyd writes, *design involves making it, then trying it out* (2020). Thus, prototyping concepts act as a safety net to evaluate first ideas. The designer can learn from the outputs of prototyping and take closer steps to a solution. To conclude, designerly thinking begins with questions that scaffold exploration and that making closely follows.

It is especially important to undertake exploration when dealing with ill-defined problems, as during uncertainty individual biases can falsely create an illusion of competence – *I know about this topic, so we will approach the problem in this way*. In short, even the most rational designer or engineer may be blinded to important details and information by their own sense of intuition. The designerly systems engineer of the hospital trolley should eventually arrive at a set of options that look much like the mechanical problem in Fig. 1. With a better understanding of the system context, heuristics can now be effective to progress the mechanical problem and improve the hospital bed for all those who interact with it.

Problem Framing in Designerly Thinking

Kees Dorst and Nigel Cross' design experiment (2001) sheds light on the nuances of designerly thinking and the importance of asking effective questions. Dorst and Cross tasked nine experienced designers to design a new railway train rubbish bin for passengers. Over 2.5 hours they observed the designers undertaking this task. Their findings are insightful to the processes of designing. Some designers questioned the purpose of the brief, *is a rubbish bin required at all? What if*…. Some designers manipulated the scope, *I should consider how the bin is emptied, hence I am designing a system too*…. This ability to question is essential to unlocking creativity and exploring possible solutions. Dorst and Cross (2001, p. 435) identify that creativity rests within the design process as an imaginative *bridge*:

> Our observations confirm that creative design involves a period of exploration in which problem and solution spaces are evolving and are unstable until (temporarily) fixed by an emergent bridge which identifies a problem-solution pairing.

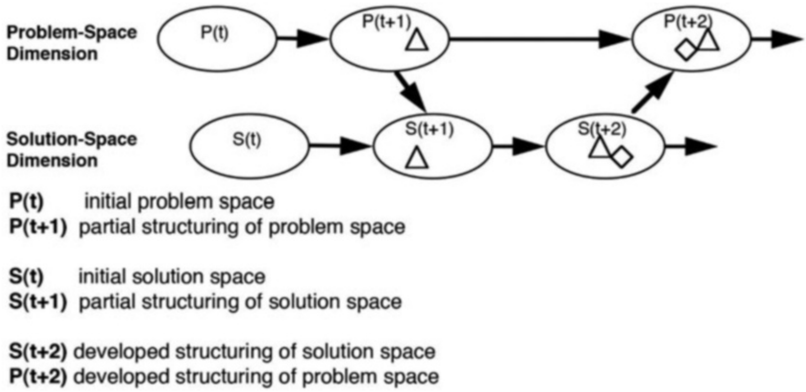

Fig. 3 Co-evolution of problem and solution (Dorst and Cross 2001)

Designers search for problem and solution pairs, often termed *frames* (Schön 1983; Dorst 2011). The activity of framing results in the co-evolution of problem and solution, a fundamental aspect of the design activity (Maher et al. 1996; Dorst and Cross 2001). This activity is visualised in Fig. 3. An initial problem is identified and framed; *P(t)*. This is often referred to as the *problem given*. A paired solution space to this problem given is also present; S(t). One of the key principles in designerly thinking is not to fixate on the first and obvious solution, but to explore the problem more thoroughly in order to arrive at a deeper understanding of phenomena – which may well be to design a mobile (yet stable) hospital trolley. Design exploration allows the designer to discover new insights and, in turn, allows for a reframed problem to emerge; $P(t + 1)$. A new subsequent solution space then also opens up; $S(t + 1)$. This process of problem-solution co-evolution typifies the designerly approach to problem solving, yet requires a reflexive relationship to the subject matter at hand via continual questioning and making.

Dorst (2017, p. 57) describes framing in the design process as vital:

> When you 'frame' a problem, you impose a view on the problem that implies a solution, or at least a direction to follow. This is often the only way to achieve a design solution, design problems can be so ill-structured and difficult that you must propose a framework (impose some kind of order) and experiment with it.

Further, Dorst identifies *experimentation* as key. The initial problem frames allow the designerly thinker to question assumptions through experiments and prototyping. When a problem and solution space are prematurely fixed, for example, the designer decides *P(t)* is the problem to solve, the creative potential of designerly thinking to realise novel solutions is stifled. Consider the following scenario:

> A design team is tasked to reduce alcohol-related crime in a city's night entertainment district. The team begin with brainstorming ideas in relation to the set task. Designer A gravitates toward ideas for greater police presence on the streets. Designer B explores ways

to reduce alcohol consumption in bars, *what about a ban on sales after a certain time?* Designer C considers how to transport people away from the area to reduce crowding on the streets. In the end, the ideas are evaluated and the concept B wins. To reduce alcohol-related crime, reduce the antecedent- alcohol.

There are three problems with this type of approach to design. First, Seidel and Fixson (2013) identify that brainstorming is ill-suited to unexplored problem statements. To ideate freely before a problem is thoroughly defined projects bias in an uncontrolled way. This is a trap for design and multidisciplinary teams. Second, the design team members would have faced difficulty detaching from their own individual concepts. Nikander et al. (2014) describe this as the "preference effect" noting that designers show a systematic preference for self-generated concepts during evaluation tasks (p. 473). Third, Dorst and Cross (2001) state this is not how designerly thinking works, "the creative design is not a matter of first fixing the problem and then searching for a satisfactory solution concept" (p. 434). As the problem has been presupposed as stable, *reduce alcohol-related crime,* there is no opportunity to allow for surprising new directions for problem-solution evolution.

This was the challenge facing the University of Technology Sydney's Research Centre, *Designing Out Crime* (reported on by Camacho Duarte et al. 2011). The research team explored the nightlife context and reframed the issue of violence as a result of a "void" created when large numbers of intoxicated patrons leave bars and clubs and enter the street at the same time. This sudden influx of people on the street pushes public infrastructure to the edge of capacity and causes tensions that can spark anti-social behavior and ultimately violence. Based on insights from exploration, the design team designed a set of system interventions; such as a night-rider *bus* to move people to a transport hub, allow them to charge phones, use Wi-Fi to connect with lost party-goers, and hydrate with water; public urinals to allow those that cannot re-enter bars and clubs after "lockout" to relieve themselves cleanly thus freeing up police officers to focus on preventing violent offences; and new lighting and seating to attract people away from bar and club entrances thus clearing sidewalks. The team's interventions thus developed from the dominant engineering systems of transport and communication to a more generally defined problem: distract the public and promote social behavior.

The design team did not constrain themselves to certain types of solutions such as *we must design new communications or new transport solutions*. Rather the team asked effective questions to probe into the peculiarities of people and stakeholders within the local environment. The team revealed unique insights like *people would like to catch the bus and ride around the route in circles, using Wi-Fi and phone charging until they could reconnect with lost friends*. Thus, the night-rider bus became more than a public transport vehicle; it became a *mobile safe house* for people who were vulnerable without realising it. This approach flipped the notion of reducing crime on its head and instead focused the team to the task of increasing public safety.

In exercising empathy and framing over optimisation, the interventions were effective in reducing crime and have survived for the most part - although the nightlife industry has been crippled by Covid-19 regulations. They illustrate that approaching a system with a restricted problem frame can be unnecessarily limiting – and can even be counterproductive. For the *Designing out Crime* team, asking effective questions was not just about uncovering needs. Asking effective questions allowed the team to detach from accepted ways of thinking about crime, public infrastructure, and engineering systems to develop meaningful interventions that did not restrict the elements that made the system valuable in the first place.

Problem-solution framing is also critical in determining different kinds of design reasoning within a design approach (Dorst 2011). Previous experiences as a designer inevitably play a role here. Lloyd and Scott (1994), in a study of engineering system design in the area of process control, showed how increased levels of experience led to progressive case-based reasoning in solving problems. This has the benefit of efficiency, in quickly transferring what has been learnt in past projects, but carries with it a danger that any previous errors may be unconsciously repeated without new questions being asked.

The failures and successes of the past encourage fixation on perceived positive directions within a design project (Crilly 2015). For example, a designer who faced difficulty integrating smart materials within a previous project may altogether avoid the prospect of experimenting with the feasibility of those materials in a new project. Further, designers have a tendency to fixate on fine details in concept stages of the design process when working beyond wireframe or sketches (Damle and Smith 2009), for example, the way in which considering the colour of the vehicle distracts the designer from deeper questions about why designing an internal combustion vehicle is the appropriate direction in the first instance.

Designerly Thinking Involves Experiential Learning

Central within the design process is learning. Beckman and Barry (2007) argue that the learning process in design is experiential. Experiential learning involves the bridging of two axes: *action and reflection* and *analysis and synthesis*. Beckman and Barry point to the theoretical developments of Kolb (1984) and Owen (1998) as lineages of experiential learning theory pertinent to designerly thinking. Kolb (1984) develops a matrix of learning styles underpinning problem solving that identifies the boundaries of experiential learning. Owen (1998) develops an understanding of how knowledge acts as a bridge between the realms of theory and practice. Where a problem is well defined, such as the mechanical lawn roller challenge (Fig. 1), a set of heuristics allow the problem solver to deduce one optimal solution. The bridge between theory and practice is accessible. When the problem is ill-defined, such as the hospital bed challenge (Fig. 2), the application of theory to practice requires experiential learning with users, stakeholders, and the system itself. The system engineer must step out of their office (and perhaps out of their comfort zone) to engage with the people and environments around them.

Jakobsen and Bucciarelli (2007) reflect on the nature of engineering education and the need for hospital bed problems as a means for authentic learning that reflects the often difficult pathway between theory and practice:

> We ought to train students in discerning concepts or laws by varying the assignments we give over contexts of much broader scope – i.e. the hospital bed compared to the roller – challenging students to discern the concept, laws or principles to be learned in more authentic as well as more varied situations. And in that way we give them the possibility for obtaining an understanding which is detached from specific contexts and thus prepare them to discern what is essential in the professional assignments they will meet (p. 299).

Within experiential learning lies an emphasis on *reflection*. Reflection is a crucial skill of the design thinker that can be undervalued within engineering fields. Designers are reflective practitioners who employ reflection-in-action in order to remain reflexive to their own work (Schön 1983). The designer steps back from their work to evaluate relevancy and build expertise.

Experiential learning is much more than individual reflection however. In group settings, surprise and reflexivity occur in social settings and are thus influenced by the norms of the environment. This has implications in innovation processes that integrate design. Dong et al. (2015) propose that concept selection in new product development involves two phases: first, evaluating the merits of a design concept through deductive analysis. In an organisational environment, deductive analysis of design concepts to assess feasibility and viability are commonplace. Second, a stage where the concept is placed into a future context to assess, "'what might be', rather than 'what is'" (p. 39). The latter stage requires innovative abduction to generate new plausible hypotheses capable of being tested. Importantly, when a deductive frame of reasoning is imposed during the evaluation of design concepts, the likelihood of that a new concept passing into later stages of the new product development process decreases. The implication is that designers must be proactive in creating environments where their concepts are evaluated in an open-minded way to anticipate biases carried by others. When decision-making is informed by designerly cognition (abduction), the merits of concepts are more likely to be appreciated. Consequently, an innovative project concept is more likely to be accepted.

An example of this relates to thinking about how an engineering system becomes optimised over time, discounting other social factors that may prove key in determining system performance. In *Car: A Drama of the American Workplace*, Mary Walton (1997) observes the design and development of the Ford Taurus, describing an episode where the position of the external rearview mirrors is determined. The problem is of a technical nature where many factors are to be considered – utility of course, but also aesthetics, noise, impact on other car systems (internal audio, air conditioning), materials, functionality, weight, etc. Should the mirror be positioned on the "sail" – the triangular area bounded by the doorframe – or on the door itself? A team of engineers test out different configurations in a wind tunnel. Walton writes of the Ford project (1997, p. 92):

> Having proved the advantages of the door location, Ehlert turned to the shape of the mirror, employing a sophisticated method of testing called a design of experiments that was useful in situations with many variables. He and a colleague spent three, twelve-hour days running wind tunnel tests on seventeen different mirror heads. With those results in hand, they worked with the studio to style a mirror that had the optimal characteristics. [. . .] The team spent a half a million dollars but at least they had the satisfaction of knowing their efforts had paid off with what could well be the quietist outside rearview mirror in the history of mankind.

But senior management weren't happy, and a "looks versus quality" debate continued until finally the two Vice Presidents intervened during a "theme decision" meeting and told the team to put the mirror on the sail. The engineers had worked hard to objectify the problem and show clearly that there was an optimal solution (deduction), but all judgments in the design process are not equal, whatever their basis. The biases of others, especially of those with seniority and power in decision-making, can often determine the final outcome of a system-related problem, despite evidence that a particular part of the system could function more efficiently.

Remedying Bias in Designerly Thinking

> "I think that. . .," "chances are. . .," "it is unlikely that. . . ."

These three phrases begin Amos Tversky and Daniel Kahneman's 1974 seminal article, *Judgment under Uncertainty: Heuristics and Biases* (p. 1124). These simple pathways to biases prompt even the most rational mind to drift toward predictable and systematic judgment errors. Key design advocate and scholar Jeanne Liedtka (2015) translates the work of Tversky and Kahneman to the benefit of designers and design(erly) thinkers. It is Liedtka's contention that design offers a way for problem solvers and organisations to identify and remedy biases that plague innovation processes. These biases can be costly, risking the firm's reputation through poor products – or even solvency through poor business choices.

Table 1 (below) shows the cognitive biases identified by Tversky and Kahneman. A short description is provided with consequences for innovation listed. This collection of biases is not exhaustive, but rather representative of relevant biases experienced by designers. An example illustrates the thought processes of whoever is affected by these cognitive biases is added by the authors of this chapter – of which you might have experienced one if not several in your engineering studies or career. These tendencies are part of human nature, for example, to project a bias based on the past may be a simple mistake that leads to larger consequences for the client and firm. What is important is knowing how these biases exist, and they can be remedied. Designerly thinking and the subsequent tool kit of design offer ways do so.

Asking effective questions is a critical activity within engineering systems design to steer away from these tabulated examples. When ineffective questions are asked, or no questioning takes place at all, the problem solver limits their access to

Table 1 (Liedtka 2015, p. 930), modified to merge remedies for cognitive bias reduction (p. 932)

Cognitive bias	Description	Innovation consequences	Symptomatic thoughts/ statements of bias	Mitigating thoughts/ statements to bias	Mitigating actions
Projection bias	Projection of past into the future	Failure to generate novel ideas	"In the past, this worked well..."	"Times have changed, let's approach this from a new perspective"	Collect deep data on others; improve ability to imagine experience of others; work in cross-disciplinary or dynamic teams; value naïve questions and challenges from less experienced people
Egocentric empathy gap	Projection of own preferences onto others	Failure to generate value-creating ideas	"I know this topic, so I will take the lead. . ."	"Please take the lead so we can explore new opportunities"	
Focusing illusion	Overemphasis on particular elements	Failure to generate a broad range of ideas	"I like the function as it is, let's focus on the color now. . ."	"Best we zoom in and out from detail to the bigger picture to make sure we do not get fixated"	
Hot/cold gap	Current state colours assessment of future state	Undervaluing or overvaluing ideas	"There is no hope trying. . ."	"Tomorrow is a new day. . ."	
Say/do gap	Inability to accurately describe own preferences	Inability to accurately articulate and assess future wants and needs	"The user told me these are the functions required, but when I observe them, I notice several more. . ."	"Let's triangulate our research to make sure we integrate as many perspectives as possible"	Improve users' ability to identify and assess their own needs; use methods that do not rely on users imagining their own needs and solutions

Planning fallacy	Overoptimism	Overcommitment to inferior ideas	"This is the best idea yet. . ."	"There is always room for improvement"	Help decision-makers become better testers; work with multiple options; conduct reflection of results of real experiments
Confirmation bias	Look for confirmation of a working theory	Missing key data that would disprove the working theory	"I ran a small evaluation and my results were overwhelmingly positive. . ."	"Let's test the results of this evaluation to check for reliability"	
Endowment effect	Attachment to first solutions	Reduction in options considered	"I immediately had a brilliant idea that we ran with. . ."	"Let's step back from initial ideas, and see what else is possible"	
Availability bias	Preference for what can be easily imagined	Undervaluing of more novel ideas	"I did a quick brainstorm and these three ideas were obvious solutions. . ."	"Our earliest ideas are the starting point for prototyping"	

contextual information that can contribute to a richer understanding of phenomena as well as increased innovation (Busby and Lloyd 1999). Further, when ineffective questions are asked, or no questioning takes place at all, the problem solver limits their ability to disconnect from *what is to challenging what can be*.

Skills and Competences of the Designerly Systems Engineer

This chapter has portrayed the nature of asking effective question in designerly thinking as a means to surface and address bias. The chapter began by identifying how problem reframing can reveal alternative solution pathways. Technical problems, such as the mechanics challenge of Fig. 1, allow the system engineer to clearly relate theory and practice. When the constraints and parameters of a problem are clear and undisputed, the problem solver can confidently follow heuristics and begin engineering a solution. However, the vast majority, if not all, of systemic engineering problems don't follow this functional logic. They are based on a human context that plays a major role in the success of engineering solution and thus must be taken account of for a design to be considered a success.

When systematic problem frames are encountered, such as the hospital trolley challenge in Fig. 2 or the Sydney nightlife crime scenario, the designerly systems engineer must begin an exploration into how the systems operates, crucially including how people experience that system and the world around them. Effective questions probe how a problem can be solved in a way that benefits the greater system. For example, the widespread adoption of a superior hospital trolley across a healthcare system to create an accumulation of improvements. A designerly systems engineer might ask: *How might the hospital trolley reduce complaints or associated costs of poor patient transport? How might implementation of the hospital trolley reveal the extent of nurse shortages?* Effective questions probe the human experience which necessitates an empathic approach from the designerly systems engineer: *How can we protect young party-goers in the Sydney nightlife district who don't even realise they are vulnerable?* Together with empathy, exploration to define and reframe problems typifies a designerly approach.

The theoretical basis for design exploration is known as the co-evolution of problem and solution (Dorst and Cross 2001). Co-evolving problem and solution frames means asking effective questions to learn about complex environments around us and also suggests ways in which smaller experimental prototypes can unveil sub-problems to move the design process forward. Beckman and Barry (2007) argue that designerly thinking is experimental learning, where loops of action, insight, analysis, and synthesis occur. Reflection is thus another crucial skill of the designerly thinker that is often undervalued within engineering fields. The designer steps back from their work to consider its effect and evaluate relevancy and so builds expertise while avoiding fixation on certain patterns or concepts (Crilly 2015), thus lowering the risks of innovation (Liedtka 2015).

To conclude, the designerly systems engineer displays the following qualities in asking effective questions and mitigating bias:

- They reframe the given question to include more contextual elements.
- They show empathy with the human experience of any proposed solution.
- They think in systemic terms.
- They reflect on their own learning about the problem and how to improve it.
- They question their assumptions and draw carefully on past experience.

To learn from past experiences yet not be blinded to the biases that form as a practitioner progresses from novice to expert is a careful balancing act. Asking effective questions acknowledges that even experts do not know everything. Indeed, being able to ask effective questions, at the right time, is a sign of real expertise in designing.

Cross-References

► Choosing Effective Means: Awareness of Bias in the Selection of Methods and Tools
► Creating Effective Efforts: Managing Stakeholder Value
► Design Perspectives, Theories, and Processes for Engineering Systems Design
► Designing for Human Behaviour in a Systemic World
► Engineering Systems Design Goals and Stakeholder Needs
► Human Behaviour, Roles, and Processes
► Public Policy and Engineering Systems Synergy
► Roles and Skills of Engineering Systems Designers

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Choosing Effective Means: Awareness of Bias in the Selection of Methods and Tools

27

Jaap Daalhuizen and Björgvin Hjartarson

Contents

Abstract

Designing for socio-technical engineering systems requires that professionals, stakeholders and end-users with diverse perspectives, experiences and expertise co-create in meaningful and goal-directed processes. Such efforts typically require substantial planning, staging, execution and managing, and an important part of that is the careful selection of effective methodology to support these activities. Methodology captures key procedural knowledge that is central to both education and practice. The selection of methods and tools is a critical first step in the process of using methodology and is prone to biases that might influence such decisions for the worse. In this chapter, we provide an overview of the state of the

J. Daalhuizen (✉) · B. Hjartarson
Department of Technology, Management and Economics, DTU-Technical University of Denmark, Kongens Lyngby, Denmark
e-mail: jaada@dtu.dk; bjhj@dtu.dk

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art on the selection of methodological means in engineering systems design and the broader design literature. We do so by focusing on five aspects: i) the method user; ii) method content; iii) method selection; iv) acquisition of new methods; and v) selection aid. To link theory to practice, we review how method selection is aided in 20 online design toolkits. Then, building on a taxonomy of thinking errors and biases in cognitive science, we identify relevant biases in choosing methodological means in engineering system design.

Keywords

Bias · Design method · Design methodology · Engineering systems design · Method selection · Thinking errors · Tools

Introduction

Design methodology captures and conveys procedural knowledge about design. As the challenges in designing engineering systems become more complex (De Weck et al. 2011; Meyer and Norman 2020), selecting appropriate methods and tools plays an increasingly important role in practising a future-proof design discipline (Daalhuizen and Cash 2021). The development of design methodology has been a core part of the emergence of our field, yet the development, validation and use of methods is an understudied area in design research (Daalhuizen and Cash 2021; Dalsgaard 2017), with some recent work focusing on the use of methods (Daalhuizen 2014), method development and validation (Frey and Dym 2006; Gericke et al. 2020; Vermaas 2016) and the information that methods contain (Daalhuizen and Cash 2021). There is a critical need to understand how practitioners (ought to) select methods and tools, and to what extent they are supported to avoid and mitigate thinking errors and biases. Arguably, selecting methods and tools is critical as it represents a pivotal point in how engineering systems design projects end up being managed and executed. However, little is known about how they are selected or which thinking errors and biases are related to the selection process and their risks to performance and project success. Moreover, there now exists a vast number of methods and tools available, and engineering programs typically teach students a considerable variety of them. Thus, there is a need to develop a more robust understanding of the selection of methodological means – especially given the rising complexity of the challenges faced by engineering systems designers.

Design methods can be defined as '*formalised representations of design activity or information artefacts which function to guide or facilitate designers' thinking processes and actions in order to achieve a goal in relation to circumstances and resources available*' (Adapted from Daalhuizen et al. (2019)). This definition implies that such methods act as information carriers, either conveying how to go about specific design activities or facilitating such activities (e.g. in the case of templates or canvasses). In this sense, methods serve to influence the behaviour of their users (i.e. designers and engineers) to be more efficient or effective in reaching specific goals. It happens through the process of selection of methodological means, interpretation and processing of the information conveyed by the method and subsequent behaviour corresponding to the method's information content and appropriate to the goal(s), circumstances and resources available (in cases of successful method use).

The first step in this process, where methodological means are selected, determines to a significant extent what follows and is thus critical in the way engineering systems design projects end up being staged, managed and executed – at least to the extent that they involve the use of methodology. It is worth noting that this step does not necessarily happen only at the early stages of projects, although many projects have a planning stage where the selection of methods is a principal activity. Selection of methods can – and often does – happen throughout projects, and decisions to use specific methods are also revisited and sometimes changed. Thus, there is a need to review and organise existing knowledge about this phenomenon and to identify the potential biased and thinking errors that are relevant to the phenomenon of method selection as well as the potential risks posed when these thinking errors and biases are not mitigated.

To address this need, we review the state of the art and identify key themes regarding method selection on the broader design literature. We also present a review of popular online design toolkits to identify how they support professionals with method selection. We then identify examples of potential thinking errors and biases relevant to method selection based on cognitive science literature.

Selecting Methodological Means in Design

Selection is an initial step in the process of using methodological means. Method use emerges from the interaction between method and method user in context. The remainder of this section explores the selection phenomenon in relation to these factors before identifying where and how designers acquire new methods, which selection aid exists, and how they work in practice.

The User of Methodological Means

Engineering systems designers typically need to master a repertoire of methodological means. To select and use these appropriately and effectively, designers need to have the right skills, resources and be '*mentally equipped*' to do so through a proper method mindset (Daalhuizen 2014). A method mindset forms '*an important part of a mental framework leading to the execution of a method*' (Andreasen 2003, p. 209). In this light, methods can be characterised as '*thinking tools*' which the user practises to guide the way they think about design work and how they subsequently act. This definition highlights the need for mental processing by the designer when using a method, implying an investment in time and effort before it can be mastered or even used at all. The selection of methods thus requires mental processing and often involves an extensive period of learning how to use the method effectively.

Depending on the user's knowledge, experiences, mindset, attitude and personality, this can happen at different levels and in different ways. For example, experienced designers typically require less methodological support and are likely to use methods for different purposes and ways than a design student (Badke-Schaub et al. 2011; Dorst 2008).

When used more often, some methodological means are internalised by their users and become part of their '*mindware*', implying that the method itself at some point will not be used anymore. Other methods might be used even after extensive experience, as practitioners repeatedly go back to them. This might, for example, happen in a team context where the method is used to ensure a shared understanding amongst team members. It could also happen in the case of an expert using a method to benchmark themselves against and hone their expertise.

Furthermore, it has been shown that designers use different '*styles*' when applying the same method (Nikander et al. 2014), pointing to individual differences in their use and related idiosyncratic development of their professional identities. Designers' '*professional identity*' has been defined as having two distinct sets of elements, '*personal attributes*' and '*design skills*' (Kunrath et al. 2020). Both of which differ across designers within the same field and even the same background and training. The professional identity influences the values and behaviours of the designer, and ultimately the actions they take. During their education and professional development, methodological means contribute significantly to the development and identity of designers (Avle et al. 2017).

This mutual interaction between designer and methodological means is core to the design discipline. The influence of individual differences impacts how design students experience the use of methods, and a relevant question to pose is: '*are some types of tools and techniques better suited for people from different backgrounds, ages, gender, etc?*' (Brandt et al. 2012, p. 175). From an opposite perspective, it has been argued that designers must not cling to their preferred personal style in terms of their way of working and must adapt to using the methodology most suited to solution requirements (B López-Mesa and Thompson 2006). Both these perspectives point to the importance of selecting methods as an object of study in its own right, from the user's perspective.

The Content of Methodological Means

Methodological means convey procedural information to support practitioners in learning, executing or managing engineering systems design work. They do so as part of a broader phenomenon of method use. To function and contribute to designers' performance, they ideally contain information regarding the goal that the method is intended to help achieve, the procedure that the method suggests to reach the goal, the mindset that is required for its use, the rationale for the method use as well as the contextual framing that describes how it is to be used in context (Daalhuizen and Cash 2021). Methods often lack some of the abovementioned information, in which case designers are typically let to interpret some of the content or complement missing information with their own experience or imagination.

A method might have several goals, some explicitly stated and others implicit or indirect. For example, Brainstorming has the overarching goal of aiding in the creation of creative ideas, while it also has the implicit goals of cultivating ownership of a problem and boosting teamwork. When selecting a method, it is crucial that the goal(s) for the activity aligns with the goal(s) of the method. Methods vary in precision and ambiguity which they prescribe specific procedures to reach the stated goal(s).

The mindset of the method is important for successful application and is the described values, principles, underlying beliefs and logic of the method. Often, the core mechanism of the method is captured in the form of principles. For example, Brainstorming asks its users to postpone criticism and associate with others' ideas to generate new ideas themselves. Methods often lack a clear description of the mindset required for their use, yet it seems to be important for selection and when adapting their content in case of ambiguity or need for adaptation.

The rationale of the method is the performance-goal relationship and the motivations underlying the goals of the method. It explains why the goal is meaningful within the context of its use and is especially important when adopting a method. The framing of the method describes the context of the method use and its implications and prerequisites. These can include which stage of the design process or within which domain(s) it can be used. It further describes who and what is needed to use the method. The frame aids the user to understand what kind of situation(s) the method can be used in and is expected to be effective.

Methodological means are typically embodied in (academic) literature, textbooks, card sets, games and online publications. The quality, accessibility and usability of these vary greatly. Some publications such as textbooks like the *Delft Design Guide* (Van Boeijen et al. 2020) or *Systems Engineering* (Haberfellner et al. 2019) and method collections like the IDEO method cards (IDEO 2003) have a more uniform quality of method descriptions. Online publications usually present sets of methods and tools in the form of an interactive toolkit with different strategies for aiding in selection, such as a filter function based on desired properties (see section "Aided Selection in Practice: A Review of Digital Toolkits").

Selecting Methodological Means

The selection of design methodology is a non-trivial activity that affects subsequent design activity considerably. Moreover, selection and use are intertwined and often happen iteratively. Selection might happen as part of a deliberate and even systematic process or be an implicit choice based on gut feeling. In such cases, practitioners might not even be aware that they choose to use a specific method, or in other cases, they might consider the choice of methods a distinct task that they carefully plan and execute. An example of the former might be the almost implicit selection of a default method that a practitioner often uses and where no alternatives are considered. Another example might be using a method because it is part of a predetermined institutional methodology (see Ernzer and Birkhofer 2002; López-Mesa and Thompson 2006; Van Kuijk et al. 2019). The latter example illustrates that selecting a method can happen at the individual, project and organisational level. In this chapter, we focus primarily on method selection at the individual level and as part of the more general phenomenon of the use of methodological means.

López-Mesa and Thompson (2003) identified three reasons for why it is challenging to select an appropriate methodology when choosing deliberately. First, the quality of the description of methods and tools varies and is often insufficient to support proper selection. Second, there are many methods and tools to choose between, and the quantity of methods is ever increasing. This abundance of options poses additional challenges to the task of selecting appropriate methodology. Third, most methods in design require substantial experience with using them before a practitioner can assess its value, quality and the resources needed. The challenge of assessing methods' appropriateness at face value and the need to invest time in understanding them again pose challenges to selecting an appropriate methodology.

Further, selection can happen at different levels, each implying distinct selection mechanisms. Braun and Lindemann (2003) identified three different selection levels. First, selection can happen at the level of '*assignment to superior process*', which they call the '*classic way*'. Here, methods are selected based on the used process model, where each stage suggests appropriate methods. This impacts method selection by limiting the pool of methods to those included in the process model while also ensuring that the methods fit the overall process and are, ideally, validated to fit the process. Second, selection can happen at the level of '*assignment to method attributes*', or method content as we define it. Here, the task is analysed based on its requirements, preconditions, application conditions, boundary conditions and target conditions; thereafter, it is matched with method content. This impacts method selection by requiring more consideration and reflection by the user. Third, selection can happen at the '*assignment to elementary tasks*' level, which means the user matches a breakdown of the basic tasks with a specific method procedure. This level requires the user to have clarified the tasks at hand, which Braun and Lindemann argue is an important prerequisite. They further argue that this allows for choosing not only a single method but also to adapt and combine a multitude of methods.

The Search and Selection of New Methodological Means

A particular case of method selection is the search and selection of new methods and tools. Gericke et al. (2016) describe two distinct strategies regarding the acquisition of new methods. The first strategy is to continuously search for new methods to add value and create variation to how a designer can approach new projects. The second strategy is to only search for new methods when facing a new problem that they could not tackle using their existing approach. In learning how to use new methods effectively, students and practitioners need to gain an understanding and a preference for working with them. A decision to '*invest*' in learning and using a particular method can be triggered by, e.g. a pragmatic need, curiosity about new ways of working, top-down incentives or rules. This variety of triggers means that practitioners might be more or less motivated to use a method depending on the perceived added value it has for them. Motivation and interest of practitioners are important factors in determining whether they will select and use a specific method to their benefit (Daalhuizen et al. 2014).

Gericke et al. identified many different sources for finding new methods, including co-workers, literature (mainly textbooks), industry peers, web repositories, online communities, customer recommendations or requirements, professional working groups, academic contacts or consultancies. They also found that practitioners typically trust the suggestions for new methods from colleagues and contacts over what they might find in written sources. Trauer et al. (2021) found that many organisations do not go through a systematic selection process when considering new methods and allow their designers and engineers to use the methods they were accustomed to rather than pushing them to perform systematic benchmarking. A vital barrier during the search for new methodology is the lack of information on the efforts required to learn how to use them. This is often hindering practitioners' initial assessment of the suitability of new methods. Further, Gericke et al. highlight that methods often lack guidance regarding the contexts for which they are appropriate and the necessary prerequisites for their use.

Aiding the Selection of Methodological Means

The selection of methodological means is often a challenging and complex task in itself. In practice, experienced designers are known to have an in-depth understanding of the design process and have experience with various methods to aid with different situations, which facilitates their selection and use (Brandt et al. 2012). Underestimating the complexity of a (new) method can lead to unsuccessful projects and negative experiences for the user. Selection of methodology is typically associated with the logical evaluation of methods, such as their ability to help with efficient and effective design processes, their attributes or fit to basic tasks. In general, selection mechanisms that aim to aid selection take for granted that the user will be able to logically and rationally follow any method which fits the problem, ignoring, e.g. mindset (see section "The User of Methodological Means"). As a result, they often lack understanding of how to stage and execute the method in a real-life setting.

A crucial part of aiding the selection of methodological means implies matching a well-defined scope of the task and a vision of the desired outcome with the expected support a method can offer. This is a prerequisite for achieving a successful process planning (Blizzard and Klotz 2012). It is essential to aid in matching methods with the purpose and goal of a specific design project (Schønheyder and Nordby 2018). It also requires support to make sure that practitioners correctly understand the method's context and specific socio-technical interrelations (Gericke et al. 2016). In this light, Gericke et al. have argued that methods are often presented in a way that does not match how practitioners would search for or select them. They found that practitioners use the following criteria to select methods: availability of required resources, required expertise or competence, expected impact on the design process and product quality, expected financial benefits, expected personal benefits, management support for its use, recommendations by colleagues and peers, mentioned in the literature, supported or recommended by standards, having experience with similar methods and a good gut feeling.

Aided Selection in Practice: A Review of Digital Toolkits

To ground the above discussion on aiding the selection, we identified and reviewed twenty different online toolkits and their selection support. The toolkits were assessed based on their general properties and their selection support (see Table 1). Most of the toolkits were created by organisations such as universities, non-profits or interest/design communities. The toolkits ranged in focus, from a narrow scope like the Biomimicry toolbox containing six methods to extensive collections such as the HI toolbox with 105 different methods. On average, the toolboxes contained 49 methods. All the toolkits provided a description of the methods to a varying level of detail, and all provided some sort of selection aid. Twelve toolkits additionally provided examples of use, and nine provided templates.

We identified four different types of selection aid, characterised as:

(i) **Filtered** selection (40%) where the user can filter the pool of methods based on different parameters, e.g. required time, purpose, user involvement and process stage
(ii) Selection through **categories** (25%) where the methods are sorted into groups based on their attributes, e.g. type or development phase
(iii) Selection through **process** (35%) where the methods are organised into different stages of a design process
(iv) Selection through **questions** (10%) where questions are used to identify the purpose of the user

Table 1 further shows an overview of the high-level selection parameters for each tool. The selection parameters were assessed regarding which aspects of method content (see section "The Content of Methodological Means") they can be categorised under. Most of the toolkits used a mixture of information concerning the procedure and goal and, to a lesser extent, the rationale and framing, yet none linked to mindset. This highlights how the match between method and user is disregarded.

Thinking Errors and Biases in Choosing Methodological Means

The use of design methodology directly impacts the behaviour and beliefs of their users and their selection is a non-trivial, complex task. Thus, their selection and use is prone to thinking errors and biases. At the same time, an essential purpose of

Table 1 Online design toolkits, properties and way of aiding selection. The table additionally shows which method content the selection aid utilises. Internal logic includes goal and procedure, user interpretation includes mindset, and contextual positioning includes rationale and framing (Daalhuizen and Cash 2021). See Appendix A for the reference for each toolkit

		Properties						Selection aid					Selection based on		
#	Name	Number of methods	Describes methods	Provides examples	Provides templates/ resources	Aids in selection	Theoretical framing	Filter	Categories	Process	Questions	Selection parameters	Internal logic	User interpretation	Contextual positioning
1	Service design tools	37	✓		✓	✓	✓	✓				When, who, what and how			✓
2	Usability.gov	55	✓	✓	✓	✓	✓		✓			Project management, user research, usability evaluation, information architecture, user interface design, interaction design, visual design and content strategy	✓		
3	HI toolbox	105	✓	✓		✓		✓				Browse by category, time and group size	✓		✓
4	DESIGN KIT	67	✓	✓	✓	✓	✓			✓	✓	Inspiration, ideation and implementation (How do I conduct an interview? What tools can I use to understand people? How do I get started? How do I prototype my ideas? How do I	✓		

(continued)

Table 1 (continued)

		Properties						Selection aid					Selection based on		
#	Name	Number of methods	Describes methods	Provides examples	Provides templates/ resources	Aids in selection	Theoretical framing	Filter	Categories	Process	Questions	Selection parameters	Internal logic	User interpretation	Contextual positioning
												choose a solution to take forward? How do I make sense of what I have heard? How do I come up with ideas? How do I assess if my solution is working? How do I prepare for launch? And how do I prepare for scale?)			
5	PROJECT OF HOW	18	✓	✓		✓		✓				Group members, time available (slider) and categories			✓
6	Biomimicry toolbox	6	✓	✓	✓	✓	✓			✓		Define the challenge, biological functions and context, discover biological strategies, abstract design strategies, emulate nature's lessons and evaluate fit and function, other	✓		✓

												pathways to biomimicry			
7	Design sprints	62	✓	✓		✓				✓		Understand, define the challenge, sketch, decide, prototype and validate	✓		✓
8	Innovation toolbox	51	✓	✓	✓	✓	✓	✓				Purpose	✓		✓
9	theDesignExchange	99	✓		✓	✓		✓		✓		Research, analyse, ideate, build and communicate	✓		✓
10	UCDtoolbox	34	✓			✓		✓				I am creating a. . ., my goal is to. . ., team size, duration, man hours, type of user involvement, participants that I want to involve, data output and locations for method execution	✓		✓
11	Circular design guide	28	✓	✓	✓	✓	✓			✓		Understand, define, make and release	✓		✓
12	Design method toolkit	60	✓			✓		✓				Purpose, research/create and time	✓		✓
13	Design method finder	70	✓			✓		✓				Project phase, focus, topic and activities	✓		✓
14	All about UX	86	✓			✓			✓			All UX evaluation			✓

(continued)

Table 1 (continued)

		Properties						Selection aid					Selection based on		
#	Name	Number of methods	Describes methods	Provides examples	Provides templates/ resources	Aids in selection	Theoretical framing	Filter	Categories	Process	Questions	Selection parameters	Internal logic	User interpretation	Contextual positioning
												methods, method type, development phase, studied period of experience and evaluation/ information provider			
15	18F methods	34	✓	✓		✓	✓			✓		Discover, decide, make and validate fundamentals	✓		✓
16	Design practice methods	43	✓	✓		✓			✓			Type (analytical methods, creative generative methods, material making methods, human-centered methods and systematic methods)	✓		
17	Usability body of knowledge	41	✓			✓	✓		✓			Planning, user research, requirements methods, cognitive methods, task analysis and modelling methods, design	✓		

												methods and usability evaluation methods			
18	UX Methods Bank	43	✓	✓	✓	✓	✓		✓			Technique, what it is, when to use it and how to use it	✓		✓
19	Open design kit	17	✓	✓		✓	✓			✓		Explore, define, make and validate	✓		✓
20	DIY toolkit	30	✓		✓	✓					✓	I want to . . ., look ahead, develop a clear plan, clarify my priorities, collect inputs from others, know the people I am working with, generate new ideas, test and improve, sustain and implement	✓		
Total			**20**	**12**	**9**	**20**	**10**	**8**	**5**	**7**	**2**		**17**	**0**	**15**

methods in design is to guide practitioners to reach their goals effectively and efficiently while avoiding, for example, deviations, unproductive work, thinking errors or bias.

Thinking errors and biases describe specific types of error in our cognitive processes that result in sub-optimal performance or even failure (Stanovich 2009a). We are typically unaware of our thinking errors and biases (Rankin 2019), and one of the major causes of cognitive biases are heuristics. Heuristics function as rules of thumb in **decision-making** in the sense that they are efficient shortcuts. A well-known example is the confirmation bias which is defined as '*the tendency to seek and interpret evidence in order to confirm pre-existing beliefs, typically by emphasising or perusing supporting evidence while dismissing or failing to seek contradictory evidence*' (American Psychological Association n.d.). The selection of methods and tools themselves is prone to such biases. For example, confirmation bias might result in the choice for a method to be overly based on the practitioner's experience with the successful use of the method in the past and ignore signs of inappropriateness to the context at hand. However, methodical means rarely include support for appropriate selection or mitigation of thinking errors in their use. Therefore, there is an inherent fragility in selecting methods, and there is a need to bring together research on thinking errors and biases relevant to method and tool selection.

The following subsections identify the phenomena of thinking errors and biases and link them to the selection of methods.

Algorithmic and Reflective Thinking

Dual-process theory captures human cognition and describes how cognition occurs at two levels, often labelled as 'Type 1' and 'Type *2*'. Type 1 processing is rooted in the implicit and autonomous mind where sub-conscious thinking occurs, and Type 2 processing is rooted in the explicit and controlled mind where conscious thinking occurs. Stanovich (2009a) argues that these constitute two groups of cognitive processes, further distinguishing between *the algorithmic level* and *the reflective level* in Type 2 processes. The latter distinction is relevant to method selection as the algorithmic level is dominant in method execution, while the reflective level plays a pivotal role in the reflective and goal-directed nature of method selection (Daalhuizen 2014). The distinction between these two levels has been empirically grounded in the distinction made by psychologists between tests of intelligence and tests of critical thinking (Stanovich 2009a). That is, intelligence tests assess the algorithmic mind's performance, whereas critical thinking tests assess the reflective mind. It is worth noting that standard tests for assessing student performance typically test intelligence and not critical thinking. Such tests form a substantial part of the assessment of children as they progress through the education system and, in turn, affect whether students can access universities. Thus, although students attending university can be assumed to be above-average intelligent, there is no guarantee that they are above average in reflective and critical thinking abilities.

Studies have, in fact, shown a lack of these abilities even at prominent learning institutions (Frederick 2005; Stanovich 2009b).

The autonomous (Type 1), algorithmic and reflective (both Type 2) mind and the corresponding cognitive processes are prone to specific thinking errors and biases. As method selection can happen at each of these levels, they also have different implications for practitioners' decisions while selecting methods. We discuss the classes of thinking errors and their implications for method selection below.

Taxonomy of Thinking Errors

Stanovich (2009a, b) introduces a '*basic taxonomy of thinking errors*', wherein he identifies two main categories, '*the cognitive miser*' and '*mindware problems*'. The cognitive misers relate to a limitation in mental resources and, therefore, a tendency for shortcuts, whereas mindware problems are errors within the knowledge or processes we use for solving problems or making decisions. The following sub-sections further explore these two types of errors and their implications for choosing methodological means.

The Cognitive Miser

A cognitive miser is defined as a failure of our brains to spend cognitive resources (i.e. activate Type 2 processing) when required, either by avoiding doing so altogether or partially. Stanovich identifies three types of cognitive misers:: (i) '*default to the autonomous mind*', (ii) '*serial associative cognition with a focal bias*' and (iii) '*override failure*'.

Defaulting to the autonomous mind is a type of thinking error that relates to our resistance to engage in Type 2 thinking when required, e.g. because a new situation occurs, and we cannot rely on our past experience to produce a suitable response. Type 2 processing is cognitively expensive to utilise, and we have evolved the tendency to maximise the use of Type 1 processes (i.e. use intuition) as it can handle most of what we used to encounter. However, Type 1 processing often falls short, especially when met by complex and novel problems characterising engineering systems design. An example of a thinking error relevant to method selection is called '*impulsively associative thinking*', which Stanovich describes as referring to situations where the user blindly associates specifics of the task to a specific method without evaluating its actual applicability.

Serial associative cognition with a focal bias is a type of thinking error linked to Type 2 error. It is a failure of engaging in proper simulation (or evaluation) of alternatives as the person is '*locked into an associative mode that takes as its starting point a model of the world that is given to the subject*' (Stanovich 2009a, p. 68), hence the focal bias. A specific example of this type of error in method selection is the *framing effect*. Framing concerns the context in which something (question, problem or event) is presented, which can be subject to bias. The framing effect in terms of method selection could be explained as the designer approaching a problem without engaging in reflection and critically questioning its frame and potential underlying bias.

An override failure is a type of thinking error linked to System 2 thinking, in which a person tries but fails to override their System 1 (intuitive) response to a situation, even though they also engaged in System 2 processing and deliberately produced a potential response as well. This type of thinking error relates to a variety of biases related to method selection, among '*belief bias*' and '*outcome bias*'. Belief bias relates to people more easily accepting arguments that support their existing beliefs and values and is related to the method and user mindset. In the case of the method selection, method A is chosen because it fits with one's mindset even if method B objectively is a better fit to the circumstances at hand. Similarly, outcome bias could result in a practitioner choosing not to use a particular method that would be appropriate because a previous instance yielded poor results even though these were caused by factors other than the method itself.

Mindware Problems

Mindware can be thought of as the software of the mind and constitutes the rules, procedures, and strategies that are retrieved by the analytic system and guide our behaviour. Mindware is acquired through learning, yet in general, people do not exercise full agency over their mindware, and not all mindware serves our best interests. Stanovich identifies two distinct types of mindware problems: (i) the '*mindware gap*' where the relevant mindware is lacking, and (ii) '*contaminated mindware*' where the mindware that has been internalised is incorrect or faulty. Stanovich rephrases this quite elegantly when he writes: '*What if you don't own your beliefs, but instead they own you?*' (Stanovich 2009b, p. 161).

Mindware gaps refer to those situations where someone lacks knowledge of appropriate strategies to deal with a particular situation and/or reach a specific goal. They are often the result of a lack of education or experience. There is an obvious link to the teaching of methodology in relation to mindware gaps. They might occur when professional engineering system designers have not learned appropriate methods to deal with relevant situations or the underlying theories to understand and evaluate the relevance of a new method or tool successfully.

Contaminated mindware refers to situations where someone retrieves mindware that is faulty and will produce inappropriate or even counterproductive behaviour to reach a given goal in a particular situation. A relevant mechanism related to this category is linked to overconfidence, where a person is biased to overestimate their abilities. This is relevant to method selection as it might lead practitioners to select and attempt to use methods that are too extensive or complicated for them to use, leading to failure. Another important category is faulty or maladaptive '*memeplexes*' that contain misinformation and guide irrational thinking and behaviour. Methodological means that have been disseminated without any validation or testing or that are informed by either '*bad practices*' or are lacking any empirical basis are at risk of containing and cultivating contaminated mindware.

Conclusions

In this chapter, we frame method selection as a critical first step in method use and an important phenomenon in engineering system design. Method selection emerges from the interaction between method user and method in a context and can happen at different levels of cognitive processes. Method selection is prone to different types of thinking errors that can negatively affect the method choice. We discuss these potential effects and review and discuss how current support tools lack the support that considers potential thinking errors. This contributes to our understanding of the process of method selection in design and points to key areas of future research. More specifically, understanding how method selection can be biased points to the importance of productive reflection in design. In general, reflection enhances the motivation to learn more about cognitive bias as well as increases the perceived importance of understanding human behaviour in design (Nelius et al. 2019), including how designers' own behaviour and biases might influence the selection and use of methods. The importance of reflection and awareness of bias in method selection is also essential in an educational context. That is, reflection on ones' own biases in method selection and use should be taught more explicitly in design programs to enable students to make better method choices and improve their appropriate use. Given that reflection typically happens in a guided way (see e.g. Schön (1987)), we argue that design educators also need to understand and reflect on how they can teach about biases in method selection and use, and be aware of any potential biases that might exist in their own treatment of methods. Future research should focus on biases and the role of reflection in method selection and use.

In the context of complex, socio-technical engineering systems, in which stakeholders typically need to collaborate across disciplines effectively, the appropriate selection of methods is especially critical. When methodology is used to orchestrate and enable multidisciplinary teams and stakeholders to contribute to and work with innovation and intervention to address societal challenges, the right choice of method – and thus rigorous selection processes that mitigate bias – is paramount.

Cross-References

- ▶ Asking Effective Questions: Awareness of Bias in Designerly Thinking
- ▶ Creating Effective Efforts: Managing Stakeholder Value
- ▶ Design Perspectives, Theories, and Processes for Engineering Systems Design
- ▶ Designing for Human Behaviour in a Systemic World
- ▶ Designing for Technical Behaviour
- ▶ Educating Engineering Systems Designers: A Systems Design Competences and Skills Matrix
- ▶ Engineering Systems Design Goals and Stakeholder Needs
- ▶ Research Methods for Supporting Engineering Systems Design

Appendix: Overview of Online Toolkits

#	Name	Publisher	Publisher type	Link
1	Service Design Tools	Oblo.design, Master in Service Design, Service Innovation Academy	Research and teaching	https://servicedesigntools.org
2	Usability.gov	U.S. General Services Administration	Government	https://www.usability.gov
3	HI toolbox	Hyper Island	Business school	https://toolbox.hyperisland.com
4	DESIGN KIT	IDEO	Design agency	https://www.designkit.org/methods
5	PROJECT OF HOW	Project How	Community	https://projectofhow.com/methods/
6	Biomimicry toolbox	Biomimicry Institute	NGO/Non-profit	https://toolbox.biomimicry.org
7	Design Sprints	Google	Tech company	https://designsprintkit.withgoogle.com
8	Innovation toolbox	University of Copenhagen	University	https://innovationenglish.sites.ku.dk/metoder/
9	theDesignExchange	theDesignExchange – UC Berkley and MIT	University	https://www.thedesignexchange.org/design_methods
10	UCDtoolbox	Tristan Weevers	Research and teaching	https://ucdtoolbox.com/browse-methods/
11	Circular design guide	IDEO	Design agency	https://www.circulardesignguide.com/methods
12	Design method toolkit	MediaLAB Amsterdam and Digital Society School	University	https://medialabamsterdam.com/toolkit/
13	Design Method Finder	Hochschule für Gestaltung (University of Applied Sciences) in Schwäbisch Gmünd – (Valentin Fischer, Wolfram Nagel, Marcel Ottmann and Tino Weiß)	Non-profit	https://www.designmethodsfinder.com
14	All about UX	Allaboutux.org	Community	http://www.allaboutux.org
15	18F Methods	18F – United States government	Government	https://methods.18f.gov
16	Design practice methods	RMIT university	University	http://www.designpracticemethods.rmit.edu.au

(continued)

#	Name	Publisher	Publisher type	Link
17	Usability Body of Knowledge	User Experience Professionals' Association		http://www.usabilitybok.org/methods
18	UX Methods Bank	UX Mastery & Co	Community	https://uxmastery.com/resources/techniques/
19	Open design kit	An open community platform	Community	http://opendesignkit.org
20	DIY toolkit	NESTA	Design agency	https://diytoolkit.org/tools/

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Creating Effective Efforts: Managing Stakeholder Value

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Alejandro Romero-Torres and Maude Brunet

Contents

Abstract

This chapter reviews stakeholder value management approaches from project management and reflects on how these approaches might enrich current practices in the design of engineering systems. Projects are complex social systems involving many stakeholders, and subsequently stakeholder value management approaches have been a focus for some time. It is essential to be able to identify

A. Romero-Torres (✉)
Department of Management, University of Quebec in Montreal, Montreal, Canada
e-mail: romero-torres.alejandro@uqam.ca

M. Brunet
Department of Management, HEC Montreal, Montreal, Canada
e-mail: maude.brunet@hec.ca

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the main stakeholders, understand their needs, and engage them throughout the project. Five important project management themes related to stakeholder value creation are explored: project definition, project governance, project delivery, contractual relationships, and project outcome transfer. We argue that all of them are highly relevant when organising effective interventions in engineering systems, and many interventions will take the shape of projects. While project value is highly subjective, varies from one stakeholder to the next, dynamically evolves throughout the life of a project, and generates tensions, approaches, and practices to managing the project value's main pillars – value in context, value creation and co-creation, and value delivery and capture can support the achievement of project performance and value.

Keywords

Biases · Engineering systems · Engineering systems design · Project management · Social systems · Stakeholders · Value

Introduction

Systems are characterised by high levels of interwoven technological and social complexity and fulfil important functions in economic sectors such as transportation, health, energy, information, etc. (De Weck et al. 2011). Whereas a traditional definition of systems engineering referred mainly to the technical aspects of developing a functional and safe product at minimal cost, there have recently been calls to combine social and technological considerations. Designing engineering systems is now seen to go beyond systems engineering, as it is recognised that socio-economic complexities and externalities impact systems that were previously considered in isolation (ibid). High-level requirements are both technical and social, calling for a range of interdependent technical, managerial, and strategic competencies. Larger systems such as urban infrastructure, airports, or major transportation hubs are complex, involving multiple stakeholders with various, and often conflicting, goals (Pitsis et al. 2018). The obvious link to project management is that commonly, such systems are created or modified through megaprojects. These "systems of systems" are defined as "a distinct class of systems generally characterised as large, complex, geographically distributed, and composed of components that are significant systems in their own right" (Shenhar 1994, cited in Lagorio et al. 2017, p. 7284). Complexity therefore increases, as each system or subsystem includes different internal and external stakeholders. At the subsystem level, it might be simple enough to satisfy requirements, but additional complexities can emerge at whole system level, where requirements may compete with or contradict each other.

The professional domains of project management and engineering systems design are overlapping, crucial approaches that address complexity (Galli 2020). Recent studies, for example, find that better integration of project management and engineering design in the initial phases of product development is a critical success factor (Sharon et al. 2011; Langley et al. 2011). As noted by Zhang (2013), developing any complex product or system requires managing the social interaction of hundreds of people to make joint and consistent decisions, including R&D specialists, final users, policy experts, sales and marketing staff, regulatory institutions, and, sometimes, communities. Engineering systems design proposes strategies to conduct product, process organisation, and engineering activities conjunctly, but may confront important limitations in managing and engaging multiple stakeholders and addressing inherent social complexity (Galli 2020). While project management aims to deliver added value to the sponsor while considering different stakeholder needs, expectations, and constraints, we argue that those practices can also inform the organising and monitoring the design processes of engineering systems (Sharon et al. 2011).

Organisations pay attention to engineering design and project management processes, tools, and techniques, but often consider them separately, without making the links between them. Indeed, for many years, systems engineers and project managers have viewed their work as separate and have each focused more on their own domains than on the project as a whole and the stakeholder dynamics involved (Galli 2020). Yet, practitioners and academics recognise the need to integrate the two disciplines and a broader set of competencies, as demonstrated by the strategic alliance between the *Project Management Institute* (PMI) and the *International Council on Systems Engineering* (INCOSE) that was formalised in 2011. In this chapter, we argue that project management might offer useful approaches to address the specific needs of stakeholders to deliver added value not only for the client, but for all people and organisations involved in accomplishing projects – such as complex interventions in engineering systems. Projects are complex social settings (Bresnen et al. 2005), which require managerial actions attuned to stakeholder sensitivities. Thus, project management practices might help to foster added value when designing engineering systems interventions as projects (or even broader, as socio-technical systems), given that stakeholders are acknowledged and spaces are created to consider their concerns, ideas, and suggestions. The result is a stronger, more socially acceptable, project with greater benefits and social value.

The purpose of this chapter is to review project management approaches from the specific perspective of stakeholder value. First, we address projects as social systems and look at project value from a stakeholder perspective. Second, we review important themes in project management, focusing on the main stakeholders concerned and the types of value created. These themes, loosely inspired by the work of Cha et al. (2018) and related literature on project studies, are as follows: project definition, project governance, project delivery, contractual relationship, and project outcome transfer. Fourth, we discuss these themes in light of the value created for stakeholders. We also reflect on how our explicit or implicit believes regarding human behaviour create biases in our choice of project management approaches. We conclude by highlighting how project management practices (such as stakeholder analysis, engagement, and value co-creation) might be integrated into the engineering systems design perspective in order to create added value and satisfy the main stakeholders.

Project Value and Stakeholders

Projects as Complex Social Systems

Project management considers stakeholders as a central piece in any project. Of course, some stakeholders have more importance and power than others, notably the sponsor, client (or final user), and financier (Clegg and Kreiner 2013). Yet, it is increasingly acknowledged that engaging external stakeholders and wider project networks helps generate added value (Laursen 2018; Di Maddaloni and Davis 2017). Basically, value is a representation of benefits versus costs, yet it is a relative notion and is viewed differently by distinct stakeholders (Laursen and Svejvig 2016). Stakeholders are heterogeneous, and satisfying all (or most) of them is challenging, if not impossible (see ▶ Chapter 25, "Transforming Engineering Systems: Learnings from Organising Megaprojects" by Geraldi and Davies in this volume). Project management offers a number of processes, tools, and techniques to manage and satisfy stakeholders by assessing and understanding their perspectives, collaborating with them (Cuganesan and Floris 2020), and allowing them to play an active role in managing the project (Winch and Cha 2020). This first section introduces the project as a social system. A second section then develops the notion of project stakeholders. Lastly, the conception of value in project management is assessed in light of the perceptions of different stakeholders.

Projects are inherently systemic, as recognised when systems engineering was established as a discipline after the Second World War to govern important military and aerospace projects (Locatelli et al. 2014). Admittedly, the context surrounding the management of (mega)projects has changed since then, as these early projects had dedicated and circumscribed infrastructure, limiting interface to within a closed system (Bresnen et al. 2005). Today, projects are much more open systems that must constantly interact with their environment and adapt to new requirements throughout their life cycle (Locatelli et al. 2014; Daniel and Daniel 2018). Klein (2019), among other scholars, suggests that systems thinking encompass the complexity of projects. While conceding that some part of a project relates to technical complexity, its social complexity as well as its context also needs to be considered: "Projects are more and different than the sum of its parts, more than blueprints, schedules, budgets and people. They are social systems in their own right, with their own politics and culture. Hence, we better account for this, as well as for contextuality. Context matters" (Klein 2019, p. 322). The project's social system is complex since it encompasses both political and cultural matters (Doloi 2013).

Projects are not only social and open systems; they are also dynamic and adaptive (Bredillet 2008; Daniel and Daniel 2018). While Klein (2019) argues that systems (including social systems) like projects are robust and meant to be stable, changes are possible, as Hendry and Seidl (2003) show in their study of strategic episodes and routine practices in project contexts. Projects also connect more widely with organisations, institutions, and project networks. Researchers have developed concepts around project ecologies (Grabher and Ibert 2011) and ecosystems (Bredillet 2008).

For example, Kusuma (2014, p. 85) defines a cultural ecosystem in a megaproject as: "a temporary symbiotic compendium of interacting organisations and their institutional environment that strives to achieve coherence and consistency in executing diverse organizational processes". This dynamism generates or increases complexity in projects (Floricel et al. 2018). Many projects are inherently complex. Locatelli et al. (2014, p. 1397) highlight that a complex project environment might have at least one of the following characteristics:

- Involves several distinct disciplines, methods, or approaches
- Has major legal, social, or environmental implications
- Uses most of a partner's resources (both tangible and intangible)
- Has high strategic importance
- Includes stakeholders with conflicting needs regarding the characteristics of the product of the project
- Demands a high number and variety of interfaces between the project and other organisational entities

Project management offers strategies for organising and optimising project performance and success by considering stakeholders' complexity triggers (Floricel et al. 2016). Locatelli et al. (2014) point to the usefulness of project governance based on open and soft systems to address key stakeholder needs and related aspects such as social acceptability, the impact of procuring local content, political support, and relationships with authorities. For Bredillet (2008), projects are social and technical drivers to satisfy stakeholders and obtain their engagement. We will now turn to this notion of project stakeholders to identify main stakeholder types and address the social acceptability and evaluation of projects.

Stakeholders and Projects

Simply defined, project stakeholders are "those actors which will incur – or perceive they will incur – a direct benefit or loss as a result of the project" (Winch 2010, p. 74). An "actor" might be an individual, a group, an organisation, a government, etc. While many categorisations of project stakeholders exist, they often involve a distinction between internal stakeholders (directly or through contract involved in the project, its governance, and management) and external stakeholders (Eskerod and Ang 2017). Winch (2010, p. 75) identifies stakeholders for construction projects based on these categories:

Internal stakeholders

- Demand side: Client, financiers, and client's employees, customers, tenants, and suppliers. On the demand side, it is important to distinguish between the project sponsor (assuming political leadership), the client (who designs the requirements and most often pays for the project), and the users of the project (who benefit from the project outcomes, the "beneficiaries") (Francisco de Oliveira and Rabechini 2019).

- Supply side: Architects, engineers, principal contractor, trade contractors, and material suppliers. Sometimes, a temporary organisation is set up for the project, which might include members of the demand side (most often a permanent organisation) and several suppliers (Sydow and Braun 2018). This is the case for most major and megaprojects, for example, the London Olympics (see the ▶ Chapter 25, "Transforming Engineering Systems: Learnings from Organising Megaprojects" by Geraldi and Davies in this volume).

External stakeholders

- Private: Local residents, local landowners, environmentalists, conservationists, archaeologists, and non-governmental organisations
- Public: Regulatory agencies, local government, and national government

These stakeholders each have distinct expectations (and understandings) of the project, which might change or evolve throughout its life-course, and need to be managed accordingly. Stakeholders in a project are multi-causal, interdependent, and polycentric, thus creating social complexity (Klein 2019). Boutinet (2010) suggests several actor types as stakeholders in a project: the owner, the resource actors, the confronting actors, the conflicting actors, the indifferent actors, and the debtors (including the final users). One of the most widely used tools in project management to engage these actors is project stakeholder analysis, which helps determine the interests, power, and legitimacy of various stakeholders (Eskerod et al. 2015a). This involves conducting an assessment, ideally at the front end of a project, and developing management strategies adapted to different stakeholders. These can range from collaborating with them, to informing them, ignoring them, consulting them, and more. Project stakeholder engagement is now a lively stream of the field, and several researchers highlight the need for more studies of this social complexity (Eskerod et al. 2015a), including inter-organisational networks (Cicmil and Marshall 2005), the role of trust between project actors (Swärd 2016; Francisco de Oliveira and Rabechini 2019), and pluralist decision-making (Stingl and Geraldi 2017). While the approach used to manage stakeholders can be either instrumental or normative (ethical), several recent studies find that a normative approach enhances overall performance of the project (Eskerod et al. 2015a).

Lately, research around external project stakeholders, such as local communities and civil society more broadly, has been conducted in project management and more specifically around megaprojects (Derakhshan et al. 2019). Social acceptability (also termed acceptance or social license to operate) is gaining increasing attention in project studies and considers mostly external stakeholders. Baba and Mailhot (2016, p. 19) define social acceptability as "an incremental process of coming together that allows actors in conflict situations to acquire learning that is conducive to subsequent reconciliation [. . .] that leads, when conditions permit, to an innovative and lasting compromise". For example, Cuganesan and Floris (2020) investigate the role of perceptions of community engagement in an infrastructure megaproject. Locatelli et al. (2017) find that once the constraints imposed by environmentalists and regulatory bodies are overcome in large transport infrastructure projects, they are likely to be completed successfully, which in turn increases their acceptance at local and national levels. Greater inclusiveness of project stakeholders might improve project performance, notably when local community opinions are sought in the initiation phase of the project and when there is monitoring of project impact at the local level (Di Maddaloni and Davis 2017). Yet, Eskerod et al. (2015b) explain that while including external stakeholders in a project increases the likelihood of generating stakeholder engagement and satisfaction, it also risks causing a loss of focus in the project or creating expectations that cannot be met. External stakeholders must be managed strategically, according to their resources and organisational power, in order to increase project performance (Ninan et al. 2019). Ultimately, the project, its management, and outcome face a broad "ecosystem of evaluations" much larger than the traditional "iron triangle" project evaluation: on time, on budget, and to prescribed specifications (Lehtonen 2014). For example, social media was recently found to impact strategic decision-making in an infrastructure megaproject (Lobo and Abid 2020). Organising external stakeholder engagement in a project requires governance-based solutions, value-based solutions, and dynamism-based solutions (Lehtinen and Aaltonen 2020).

Summarising the discussion so far, project stakeholders are multiple, with different interests, resources, and expectations, and they introduce social complexity into projects. We will now look at the question from the opposite angle to explore what value a project might bring to stakeholders.

Value in Project Management

As projects play an important role in contemporary society and in organisations, value creation in projects and project-based organisations has become an essential research stream in the field of project management (Laursen and Svejvig 2016). Value is generally seen as a representation of the benefits versus the costs incurred by different stakeholders (Laursen and Svejvig 2016). Miterev et al. (2020, p. 113) propose a definition of value that differs between the various project stakeholders: "we define value as the perceived ability of a product, service or system to meet the target user/stakeholder needs". Martinsuo et al. (2019, p. 631) define the delivery of value in projects as the "activities, processes, and strategies that organizations use to produce benefits at a reasonable cost, either in specific projects or through project business in general". Martinsuo (2020, p. 1) explains that value management in project business "deals with the means to identify stakeholders' explicit expectations about what is of worth/worthy and convert these expectations into plans and measurable benefits (through project activities)". She distinguishes between *value as worth* and *value as belief*. According to her, value as worth emerges through the project life cycle in distinct activities concerning value:

expectation; negotiation; (co-)creation; delivery; use, capture, and diffusion; and disposal. She highlights three main challenges regarding value as worth over the project life cycle:

- Subjectivity: Multiple stakeholders with different backgrounds and interests
- Dynamics: Projects in their context, project life cycle with various phases and events
- Tensions: Multiple value dimensions with different priorities; expected versus achieved value

Martinsuo (2020, p. 6) defines values as belief as "attention on espoused values versus values in use, and how each aspect of value is constructed at different levels (group, organisation, network...) and enacted in behaviour". Some values given as examples include economic, environmental, social, technical, and aesthetic/symbolic.

Table 1 Criteria for assessing social values. (Adapted from Doloi 2013, p. 299)

Subsystem of social value	Social value	Description
Economic	Capital performance	The economic sustainability of the project
	Internal human resources	Social responsibility toward the workforce in the project
	Service provision	The service and infrastructure provided by the project to meet user needs and maintain a level of satisfaction, including the right technological choices
Political	Regulatory compliance	The project's level of conformity with current regulations, including certification, public safety, and fair work requirements
	Intra- and inter-generational equity	The effective choices pursued to reduce the gap between different groups of people
Political and cultural	Information provision	The quantity and quality of information shared with stakeholders
	Economic welfare	The external economic impact of the project, including contribution to GDP, taxes, foreign trade opportunities, etc.
	Socio-environmental performance	The project's contribution to environmental improvement, including reducing greenhouse gas emissions, reducing non-renewable energy use, protection of endangered species, etc.
Cultural	Community development	The social and institutional relationships with the community, including cultural heritage preservation, social cohesion, protection of human rights, etc.
	Stakeholder influence	The degree to which the project actually incorporates stakeholders' opinions into operational decision-making

A categorisation of the main criteria for assessing social values in projects is offered by Doloi (2013), who presents social value through three functional subsystems: economic, political, and cultural. Table 1 summarises these criteria and relates them to the main subsystem involved.

In an editorial introducing a special issue of the International Journal of Project Management on "Delivering value in projects and project-based business", Martinsuo et al. (2019) classify the core aspects of delivering value into three recurring themes: (1) value in context, (2) value creation and co-creation, and (3) value delivery and capture. Value in context challenges many established theories and practices aimed at maximising value creation and capture, as it recognises that value is a contextually embedded social construct. Value creation and co-creation then highlight the dynamics of co-construction, as project actors engage in the project, co-construct interactions, and contribute their perceptions. Lastly, value delivery and capture focus on how organisations and projects achieve value through project-related activities, for example, by upholding larger environmental, financial, social, or systemic values. Having reviewed the main conceptualisations of project value for stakeholders, we now investigate how project management practices and tools might support stakeholders in defining, creating, and capturing value.

Project Management Practices to Create Stakeholder Value

As explained above, projects are complex arenas that involve, and create value for, multiple stakeholders. Project management as a field took root only a few decades ago as a way for businesses and organisations to organise work around projects and to understand the critical need to communicate and integrate work across various stakeholders (Morris and Pinto 2007; Morris 2013). For many years, project management practices focused on managing efficiency constraints such as time, cost, and scope (quality is usually included as a substitute for or component of scope), also known as the project management triangle (Kerzner 2017), triple constraint (PMI 2004), or iron triangle (Atkinson 1999). In this limited conceptualisation of control, project decisions and actions are dictated by these constraints. There are usually one or two fixed constraints defined by the project sponsor, while the third depends on the strategy adopted for managing the project (Kerzner 2017). During project realisation, project managers base decisions on these interrelated constraints, since a strain in one will affect the others. Attempts to reduce a project's duration may increase its cost and decrease its scope. Cutting a project's budget can have a disproportionate effect on project scope and timescale.

Empirical evidence shows that limiting project management practices to efficiency constraints cannot guarantee project success (Ogunlana 2010; Dimitriou et al.

2013; Kerzner 2017). Projects can respect time, cost, and scope constraints but still not accomplish their objectives. Ogunlana (2010) suggests that the project management triangle model represents a limited view of the project context since it focuses on just three aspects and ignores many more subjective and context-specific issues. For instance, it does not consider that project value is multidimensional and can evolve over the project life cycle. Dimitriou et al. (2013) state that efficiency constraints fail to consider important success criteria relating to emergent properties of what is produced by the project.

Most research on project success concludes that projects, as social arenas, should consider stakeholders' perceptions when evaluating the success or failure of a project. Turner and Zolin (2012, p. 87) explain that "success is perceived [by stakeholders] not just by the traditional view of completing the work to time, cost, and quality, but also by whether the project delivers the desired outcome", including stakeholder satisfaction (Ogunlana 2010), new capabilities (Miles and Wilson 2004), and added value (Mir and Pinnington 2014). Stakeholder satisfaction and the achievement of benefits therefore become effectiveness constraints within project management practices.

The effectiveness and efficiency of projects may be enhanced by introducing practices that optimise the management of organisational resources. Thus, project management can support the achievement of project and organisational goals for creating value to stakeholders (effectiveness) and assuring stakeholders that resources are being managed efficiently.

Effectiveness and value creation for stakeholders have generated debate between different approaches to managing projects. While the traditional waterfall (or predictive) approach considers that projects are managed according to a fixed scope and approximate schedule and budget, the agile (or iterative) approach recognises that stakeholder value can change or evolve during the project and proposes managing projects according to a firm schedule and flexible scope (Bick et al. 2018). Agile project management follows a plan, but adopts an iterative process that is quite different from the traditional model. One key difference is the idea of welcoming changes to the project at any phase in the project development life cycle. Other hybrid approaches are sometimes used; however we will not be covering them in this chapter.

Inspired by Cha et al. (2018), we will now examine project management practices (aligned with traditional and agile approaches) used to manage technical and social complexity in projects, looking at five categories of practice: project definition, project governance, contractual relationship, project delivery, and project outcomes transfer. Cha et al. (2018) use these categories to define stakeholders' roles in managing value. They consider two main stakeholder groups: (1) the sponsor (or client) and its stakeholders, representing the permanent organisation looking to add value to its organisation, and (2) the project provider or contractor, often representing a temporary organisation (project team) that provides its expertise to execute the project and deliver project outcomes. We discuss the contribution each of the five categories of practice brings to generating value based on Martinsuo et al.'s (2019) value themes: value in context, value creation and co-creation, and value delivery and capture.

Project Definition

Project definition is the earliest phase in the life of a project. It involves the process of developing sufficient strategic information so that owners (permanent organisation) can consider options for addressing stakeholder expectations, needs, and constraints (Williams et al. 2019). This early part of the project – from the time the project idea is identified to the time just prior to the formal development phases – is also called the fuzzy front end (or just front end) (Smith and Reinertsen 1998). The fuzzy front end is described as the messy "getting started" period of product/service development, when the concept is still unclear (De Brentani and Reid 2012). Preceding the more formal project process that is defined by project management standards, the front end generally consists of three tasks: strategic planning, concept generation, and, especially, pre-technical evaluation (Williams and Samset 2010). These activities are often chaotic, unpredictable, and unstructured and may last several years (Williams et al. 2019).

Project definition is a complex and time-consuming decision-making process intended to generate, consolidate, and analyse relevant information and determine the solution to be implemented in the project (Miller and Lessard 2000). It begins with conceiving the initial idea or identifying the problem or need to be addressed. Permanent organisations collaborate with main stakeholders (mainly product/service final users) to understand what each of them really wants and needs. This includes identifying differences between expectations and needs, so as to develop a shared understanding of the problem and alternative project solutions (Williams et al. 2019). Owners typically carry out various specialist studies to establish the project concept and test feasibility. Feasibility tests determine whether the project objectives can be met with available resources, within the constraints of the operating environment (Samset and Volden 2016). Finally, owners decide whether to initiate and finance the project based on a business case that includes anticipated impacts on the organisation and long-term benefits (Williams et al. 2019). Williams and Samset (2010) state that the front-end phase is when the project exists only conceptually, before it is planned and implemented.

Several researchers have highlighted the importance of clearly defining the project to create added value (Williams and Samset 2010, 2012; Morris 2013; Edkins et al. 2013). The process of managing stakeholder expectations when defining the project's purpose generates value in context and value co-creation. The permanent organisation could work on its own to identify the context of the project and define the best solution to be implemented. However, stakeholder perspectives might then become problematic at a later stage. Collaborating on definition of the project concept enables collective identification of project objectives and supports value co-creation. As Edkins et al. (2013, p. 71) state: "[factors] that cause projects not to succeed have their origins in decisions made in the project's front end and that the front end is the part of the project that has the greatest opportunity for creating value".

Uncertainty in project definition stems from the project environment, the features, procedures and technologies of the chosen solution, and the stakeholders involved.

This uncertainty plays an important role in shaping project definition. Using a traditional project management approach, permanent organisations try to understand the sources of uncertainty, develop strategies to address them, and establish accurate and achievable expectations (Edkins et al. 2013). When adopting an agile approach, permanent organisations tend to either identify a flexible solution that allows for changes during project delivery or delay no-return decisions related to the solution (Fernandez and Fernandez 2008).

Project Governance

In parallel with project definition, and influenced by decisions made in the front-end phase, project governance establishes the mechanisms, structures, roles, and responsibilities that create conditions for collective and orderly action to achieve project purpose (Pemsel et al. 2014). Governance is based on the creation of a structure that cannot be imposed externally, but results from the interaction and mutual influence of multiple actors (Pinto 2014). Project governance involves processes and relationships and works through two major mechanisms: trust and control (Müller 2017). Governance is developed to reduce or eliminate the impact on projects of external factors such as political influence and to ensure that people are held accountable for delivering different parts of the project (Müller 2009). Bekker (2014) suggest that attention to governance enables better monitoring, accountability, responsibility, and clarity in a project.

Approaches to project governance vary (Müller et al. 2013). Narayanan and DeFillippi (2012) propose focusing on structural governance that includes a stage gate approval process, stakeholder representation, formal roles and responsibilities, quality assurance, contracts, and sign-offs. Structural governance clarifies when decisions are made and by whom. Hjelmbrekke et al. (2017) view governance as relational. It establishes mechanisms to manage stakeholder relationships, with a focus on leadership, motivation and incentives, resource allocation, conflict management (including ethical concerns), stakeholder involvement, informal relations, and communication. While no standardised project governance framework has been accepted by everyone in the field (Müller et al. 2013), certain frameworks have been developed and promoted by the Project Management Institute (PMI), the Association for Project Management Group (APMG), Prince II, and the UK HM Treasury.

The permanent organisation is responsible for project governance, in particular for monitoring service providers (and/or the temporary organisation) and project management, which is, in many cases, mandated externally (Müller 2009). Generally, the sponsor is considered the main source of authority (Crawford et al. 2008), followed by the project management committee on which the sponsor is a member (Müller 2009). This committee serves as the mechanism for implementing project governance and provides the link between the permanent organisation and the temporary organisation. Normally, this committee is made up of decision-makers who have managerial authority; however, other participants, such as managers of domain experts, can be added as necessary (Müller 2009).

Project governance also involves creating value for the larger organisation. It can support value in context, value creation and co-creation, and value delivery and capture. Governance practices focus on aligning projects to the organisation's strategic plan to enable a solid understanding of the context and support decisions that generate value (Bekker 2014). Thus, governance enables the establishment of a clear decision-making process and clarifies stakeholder roles and responsibilities to facilitate collective decision-making and action (Pinto 2014). Finally, governance enables value delivery and capture, since it defines methods to assess planned against actual results, identify deliverables, measure outcomes, and improve risk management.

Project governance can also support decisions around selecting the best management approach for the project (traditional or agile) and the most appropriate structures and coordination mechanisms for that approach. However, governance must allow flexibility, since several factors can change during project delivery (inflation, new regulatory framework, change of government, etc.). A flexible governance framework is essential to adapt not only to the life cycle of a project but also to the specific needs of each project (Miller and Lessard 2000).

Project Delivery

Project delivery focuses on developing project outcomes (product and/or services) that will be delivered to the owner for value creation. This stage describes the classic process presented in the Project Management Body of Knowledge (PMBOK®) (PMI 2017), starting with the project charter or business case, proceeding to planning, executing, monitoring/controlling, and ending with the delivery of project outcomes to the owner (Romero-Torres and Martinez Sanz 2018). This stage is usually under the responsibility of the temporary organisation – either internal or contracted externally – that receives the mandate to realise the project. In public procurement procedures, a call for tenders is launched in order to retain the service provider(s) to execute the project in accordance with the contract signed between the parties (see section "Contractual Relationships"). While the owner ensures management of the overall project, internal or external suppliers each manage their own "project", which is most often on a smaller scale as the overall project is divided into multiple project contracts (notably for professional services, feasibility studies, construction, surveillance, etc.).

Project delivery supports value creation or co-creation and indirectly supports value capture. Project delivery focuses on creating the project outcomes that will deliver value after they are transferred to the permanent organisation (see section "Project Outcomes Transfer"). The co-creation of value is possible in agile environments where the final user can actively participate in the elaboration of outcomes by providing continuous feedback or executing specific outcome tasks.

Project delivery considers technical, contractual, relational, and managerial procedures to create project outcomes in line with project definition and project governance. Project delivery has been documented and discussed extensively in the literature, including in research work on success factors and best practices, and in standards or practitioner guides such as PMBOK®; ISO 21500, Guidance on Project Management; IPMA, Project Excellence Baseline; Prince II, Axelos UK. These standards and guides principally cover practices, principles, enablers, and roles and responsibilities to manage the project from the time it is defined (see section "Project Definition") until deliverables are accepted; these include oversight of project scope, schedule, cost, quality, communications, risk, stakeholders, resources, and procurement management.

Project delivery can use predictive (traditional) or iterative (agile) development approaches. To accommodate change, project delivery may opt for an agile strategy that involves repeated phases, or sprints, toward a partial solution and includes feedback loops (Fernandez and Fernandez 2008). Each phase delivers a particular component of the project, which over time will coalesce in a final collective product. Several methodologies can be used to deliver projects through use of an agile approach, such as Scrum, Kanban, Extreme Programming, or Crystal (Tonchia 2018). They have been well received by industry because they focus mainly on creating value for the owner and final users (Denning 2018).

However, project management standards, guides, and methodologies are usually generic and abstract, and more knowledge is needed on how to use them properly (Hermano and Martín-Cruz 2019). Researchers have identified several shortcomings (Hübner et al. 2018). For instance, Varajão et al. (2017) considers that standards do not correctly account for issues that can hinder project success, such as risk management and stakeholder engagement. Cha et al. (2018) and Winch and Cha (2020) find that project delivery standards present a limited vision of the project management field, since they do not give the project owner an active role in managing projects beyond the project delivery boundaries. Furthermore, standards and guides do not include the main practices used to create value (Cha et al. 2018).

Contractual Relationship

As seen in the above section, value creation depends on two distinct actors: the permanent organisation (also called owner), responsible for project definition, governance, and transfer of outcomes to operations, and the temporary organisation (which might include one or several suppliers) responsible for project delivery. While the situation varies from case to case, most of the time the owner's project is much larger than the individual contracts awarded to suppliers to execute portions of the overall project. In this sense, service providers have their own "project" to manage (delimited by the contractual framework), which is part of the owner's broader project. The contractual relationship acts as a bridge between project governance and project delivery (Chakkol et al. 2018), where project governance aims to coordinate supplier activities to add value during project delivery by supervising formal and informal contracts and monitoring the relationship between the owner and suppliers, notably with the support of conflict resolution processes (Pinto 2014).

Adopting a collaborative approach to contract management can trigger value co-creation and value delivery and capture (Jobidon et al. 2018). Collaborative contractual relationships such as integrated project delivery (IPD) or alliancing (Walker 2018) enhance value co-creation by enabling involvement of and collaboration among participants throughout all project phases, especially during project definition. In addition, the main stakeholders also participate in value delivery and capture, since IPD supports shared responsibility for project benefits once outcomes are delivered. A collaborative relationship is also amenable to agile approaches, because it enables flexibility and engagement among project participants (Bick et al. 2018) that can help prevent cost overruns, delays, and quality issues (Walker 2018).

Contractual relationships trigger transaction costs that can negatively impact the project's added value. Traditional contracts are associated with costs such as asymmetry of information costs, bargaining-decision costs, and policy enforcement costs (Li et al. 2013). These can increase if cohesion between owner and suppliers is absent (Floricel et al. 2011). For instance, they may blame each other for contract difficulties, question not only technical solutions but also agreements between, prompt certain participants and stakeholders to rethink their own interests, question the arrangements that made the project possible, and demand new benefits (Floricel et al. 2016). To decrease transaction costs, owners and suppliers can develop proactive and reactive strategies. Floricel et al. (2011) propose a proactive approach to cultivate trust and increase voluntary adherence to the project objectives. For instance, early inclusion of all key stakeholders enables development of common processes and tools, especially for decision-making and problem solving (Haaskjold et al. 2019). On the other hand, reactive approaches can prevent misunderstandings and conflicts by including preparation for the use of legal levers to force participants to cooperate (Floricel et al. 2011).

Project Outcomes Transfer

The transfer of project outcomes (i.e., project products) to operations (i.e., often the project beneficiary) is a key element to be considered when managing a project. However, most organisations neglect this important step or fail to correctly manage the stakes involved in outcome transfer. The project performance literature suggests that organisations often succeed in obtaining the deliverables from projects, but fail to achieve the desired operational and usage benefits (Flyvbjerg 2009; Zerjav et al. 2018). Project outcomes transfer (or the project back end) includes processes to support the sponsor or permanent organisation's ability to integrate project outcomes into operations (Artto et al. 2016). The transfer of outcomes from the project to operations is often overlooked since this phase unfolds at a different timescale than phases of project definition, planning, and delivery and might involve stakeholders beyond the project team. Often, the transfer of results to achieve project benefits is only measured months or years after finalising the deliverables.

Morris (2013) consider that projects only generate value when stakeholders on the operational side of the organisation use project outcomes. Project outcomes transfer thus contributes to value creation and co-creation and, most importantly, to value delivery and capture. Even if project outcomes are created during project delivery, value is only created during their transfer to operations. Stakeholders (as final users) must incorporate project outcomes into their habits in order to obtain project benefits. Change management practices must therefore be included in project management (Hornstein 2015). Project outcomes transfer contributes to value delivery and capture by introducing benefits management practices as defined in *Benefits Realization Management: A Practice Guide* (PMI 2019), the MoV® guide from Axelos (2010), or *Managing Benefits: Optimizing the Return from Investment* (Jenner et al. 2014). These practice guides help organisations identify value and manage project and operations processes to deliver value and, finally, to capture value.

Transfer may be the final element in the life cycle of a project; however the challenges of transferring project results need to be considered right from the project definition stage (Artto et al. 2016). Permanent organisations must manage the transition of project outcomes, including change management and benefit realisation management, i.e., ensuring that the strategic goals of a project translate into planned benefits (Svejvig and Schlichter 2020). These last two elements are managed throughout the project and even after the end of the project, in order to support operations in the appropriation of deliverables (Morris 2013). More specifically, change and benefits management must be defined and planned for during project definition (front end) and be managed during project delivery and the transfer of deliverables to operations. The temporary organisation can also participate in transferring outcomes, either by supporting the permanent organisation to manage change and project benefits or by evaluating project performance in general and its own performance in particular.

New practices have emerged to support the transfer of project outcomes to operations, especially in IT agile environments. DevOps is an approach to enable continuous delivery of project outcomes to operations (Bierwolf et al. 2017). A fundamental assumption challenged in DevOps is that achieving frequent and reliable project outcome transfers requires a stable production environment (Banica et al. 2017). DevOps includes continuous exploration of new project opportunities, continuous integration of project outcomes into operations, and continuous deployment of project outcomes to deliver and capture value (Banica et al. 2017). This new approach is attractive in dynamic organisational environments and when stakeholder needs and expectations may vary over time.

Discussion

Creating Value

Examining the value of a project is highly important and helps the organisation identify benefits for stakeholders, measure success, and make improvements to the overall efficiency of a project. As we have emphasised throughout this chapter, the value of a project reflects its ability to address the explicit and implicit needs of

Table 2 Project practices for creating value

Categories	Practices	Standards and practice guides
Project definition	Definition of problem/opportunity Solution analysis Alternative analysis and evaluation Feasibility studies Definition of solution Case study/mandate definition	*PMI guide to business analysis* – PMI BABoK® guide – International Association of Business Analysis
Project governance	Organisational project management Definition of roles and responsibilities Definition of decision-making process	Organisational project management – PMI *Governance of portfolios, programs, and projects: A practice guide* – PMI Organisational competence baseline – IPMA
Project delivery	Integration management Scope management Schedule management Cost management Quality management Resource management Communication management Risk management Stakeholder management	Guide PMBOK® – PMI ISO 21500 – Guidance on Project Management Project excellence baseline – IPMA Prince II – Axelos UK Agile practice guide Scrum method XP method Kanban method
Contractual relationship	Supplier management Contract management Procurement management[a]	Local and sectoral standards and practice guides depending on the type of projects, governmental and organisational regulations
Project outcomes transfer	Benefit realisation management Organisational change management Knowledge management	*Benefits realization management: A practice guide* – PMI Guide MoV® – Axelos *Managing benefits: Optimizing the return from investments* – Jenner *Managing change in organizations: A practice guide* – PMI

[a]Procurement management is included in most project delivery standards and guides; however, procurement practices focus on managing the contractual relationship

stakeholders, through explicit and implicit project functions (Too and Weaver 2014). In this chapter, we propose five main categories of practice to manage stakeholders and create value: project definition, project governance, project delivery, contractual relationships, and the transfer of outcomes to operations. Table 2 presents these categories and the main practices, standards, and guides related to each. These practices permit the integration of stakeholder expectations and work to generate value (Artto et al. 2016; Morris 2013). Integration can be obtained by reinforcing social communication and interaction among stakeholders who benefit from value creation.

Stakeholder identification and stakeholder engagement processes are proposed in professional standards and professional guides, such as PMBOK®, PMBOK®, ISO 21500, or Prince II, to create and co-create value during project delivery. However, engineers and project managers must also develop approaches to manage value at the front end and back end of the project. At the front end, project identification practices allow for analysis of the project context and stakeholders in order to define the project's *raison d'être* (problem, need, or opportunity) and identify the best solution to create value. Project governance and contractual relationship practices establish a framework for decision-making and managerial action that help assure value creation and co-creation and value delivery and capture. Good governance is essential to providing sustainable value for the organisation and its stakeholders (Müller 2009; Too and Weaver 2014). At the back end, outcomes transfer to operations allows the created value to be captured and delivered since it can be achieved if the "project's result (product, service or result) is used by the organization to generate the intended outcomes and the outcomes enable the realization of a range of expected and other benefits" (Jenner 2015, p. 17).

Value is relative to the perception of each stakeholder in the project process. Although there are many stakeholders involved, we identify two primary stakeholder groups in value creation: permanent and temporary organisations (see Table 3). Even if the temporary organisation is crucial in the creation and co-creation of project outcomes and thus supports value creation, the prime responsibility for value should remain with the permanent organisation. Project managers, systems engineers, and other project team members should help their permanent organisation adequately

Table 3 Project management categories, responsibility and types of value

	Value in context	Value creation and co-creation	Value delivery and capture	Responsibility for value creation
Project definition	x	x		Permanent organisation
Project governance	x	x	x	Permanent organisation
Project delivery		x		Temporary organisation, supported by permanent organisation
Contractual relationship		x	x	Permanent organisation and temporary organisation
Project outcomes transfer	x	x	x	Permanent organisation, supported by temporary organisation

define the project, govern it, and transfer project outcomes to operations in order to deliver and capture project value.

Co-design and open design (see the chapter on this topic in this volume) are approaches that could also generate value for stakeholders. These focus on designing a solution through interaction with the final user. These approaches are mostly used in the project definition stage, where a concept is developed and several alternatives are evaluated. In this case, the final user can help the project team better understand the problem or opportunity related to the project, identify which solution will generate most value, and consider final user expectations for project outcome transfer. In agile approaches, collaborating with the final user for project delivery can also generate more value since user feedback and changes in user expectations are directly communicated to the project team.

Biases from Human Behaviour

As mentioned before, value is defined, created, and captured by social communication and interaction among stakeholders in the permanent and temporary organisation throughout the entire project process, from definition to project outcomes transfer. However, because of its subjectivity and dynamic nature, the project value depends on the perception of each stakeholder. Their perception is deeply influenced by their engagement to the project and by their abstract thoughts and relationships, individual attributes and circumstances, personal interactions, cultural identity, and available information (Stingl and Geraldi 2017).

Stakeholders' perception could then generate biases and errors in the project decision-making process. Biases are related to the implicit or explicit tendency, inclination, or prejudice toward or against something or someone that involves unconscious, simplified strategies and routines that stakeholders rely on to assist with their decision-making process (Elsbach and Stigliani 2019). Biases appear when tendencies, inclination, or prejudice is inappropriately applied to a scenario (Stingl and Geraldi 2017). Then, human error is related to the behaviour of ignoring or misunderstanding information so that project decisions are not entirely based on facts (Stingl and Geraldi 2017). Both bias and human error can then influence how the value will be perceived by each stakeholder and then how value is contextually defined, co-created, delivered, and captured.

Different perceptions, biases, and human errors could also influence the social interactions among stakeholders, generate tensions, and influence the value creation. Indeed, stakeholders' influence is deeply related to their ability to mobilise their relational skills (soft skills) for communications, negotiations, motivation, leadership, and empathy (Jarrahi 2018). Stakeholders use their soft skills to recognise and convey emotions, interpret and reason with emotion, use emotions effectively to promote and influence their own and others' thinking, and manage feelings effectively (Jarrahi 2018). The stakeholder influence is a double-edged sword for value creation. Using relational skills could strengthen collaboration and engagement between stakeholders when these abilities are used to influence stakeholders to a recognised and accepted common goal (here, a common vision of value). However, stakeholders with a high-power level, such as the sponsor, steering committee, or even the project manager, could use their abilities and their power to underestimate and/or dismiss legitimate value perception from low-power stakeholders (Clegg and Kreiner 2013).

Project managers and engineers can use their relation skills to facilitate healthy social interactions among stakeholders to lower possible tensions generated around the value. In particular, they can mobilise their emotional intelligence to develop stakeholders' potential, build high-performing relationships, appreciate diversity, challenge different stakeholder perceptions and priorities, inspire and motivate individuals and teams, implement change, and adapt to dynamic social settings (Davis 2011; Clarke 2010). This emotional intelligence can support the project team to navigate throughout permanent and temporary organisations with their related culture and politics. In project context, organisation politics are used to influence or change the project direction (here, project value) according to the desires of stakeholders with a high-power level (Pinto 2000). Conflicts can then arise since stakeholders are in competition for resources and recognition (Mele 2011). The project managers and engineers must then understand the connection between politics and stakeholders and identify sources of power to avoid negative influence on the value creation.

Finally, to minimise stakeholders' biases, errors, political games, and conflicts, project management practices for value in context during the project definition (see Table 3) remain capital to identify, clarify, and recognise a common perception of value among the different stakeholders. Then, this common perception of value (value in context) can be employed to govern and direct the following categories of practices in project management, project governance, project delivery, contractual relationship, and project outcomes transfers, and to facilitate the other types of value: value creation and co-creation and value delivery and capture.

Conclusion

This chapter highlights that project stakeholders are numerous. Although some are marginal and might not have the power and assertiveness to make their voices heard, including them in the project process is beneficial as it generates higher social value, limits resistance, and enhances the project's social acceptability (Di Maddaloni and Davis 2017). Greater inclusiveness of project stakeholders, notably in project definition, governance, and project outcomes transfer, requires resources and commitment, yet generates improved project outcomes, increased organisational legitimacy, and less social resistance (Eskerod et al. 2015b).

Managing project value is far from simple, given the subjectivity of the concept of value (which thus varies between stakeholders), its dynamic evolution across the project life cycle, and tensions between expected and achieved value at project delivery (Martinsuo 2020). However, several approaches and practices are useful to manage the main pillars of project value: value in context, value creation and co-creation, and value delivery and capture. As Table 3 suggests, value in context is inherently important at both the front end of the project and at the back end during outcomes transfer; value delivery and capture are essential to consider in categories of practice such as governance, contractual relationships, and outcomes transfer. However, value creation and co-creation are central to all categories and bear intrinsic importance that cannot be neglected if the project is to succeed. Co-creation can also include value in context since creating with stakeholders, and specifically with the sponsor and final users, allows the project to be modelled on stakeholder needs and expectations. Special attention arises in the value creation process since it can be influenced by human biases, errors, political games, and conflicts. Project managers and engineers should develop their relationship skills and project management practices to create a healthy environment for the project and the value creation.

Project management as a field of study supports the ability to negotiate the complex socio-technical interplay of projects. Bridging this field with engineering systems design stands to enhance both theoretical fields, as well as provide practical support for achieving project performance and value (Locatelli et al. 2014).

Cross-References

▶ Engineering Systems Design Goals and Stakeholder Needs
▶ Engineering Systems Interventions in Practice: Cases from Healthcare and Transport
▶ History of Engineering Systems Design Research and Practice
▶ Risk, Uncertainty, and Ignorance in Engineering Systems Design
▶ The Evolution of Complex Engineering Systems
▶ Transforming Engineering Systems: Learnings from Organising Megaprojects

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Ethics and Equity-Centred Perspectives in Engineering Systems Design

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Wiljeana Jackson Glover and Rachele Hendricks-Sturrup

Contents

Abstract

Ethics and equity-centred perspectives are critical for the advancement of engineering systems design. The characteristics of engineering systems, namely, their high degree of technical complexity, social intricacy, elaborate processes, and their aim to fulfil important functions in society makes them highly vulnerable to several ethical dilemmas and inequities that can lead to suboptimal performance. This chapter first highlights the varying ethical considerations within the literature, including distributive justice, procedural justice, safety ethics, privacy and trust, autonomy, and sustainability. Next, we discuss the influence of assessing ethical behaviour at the micro-, meso-, and macro-levels of analysis and five ethical themes present in the current engineering systems design literature:

W. J. Glover (✉)
Operations and Information Management Division and the Kerry Murphy Healey Center for Global Healthcare Entrepreneurship, Babson College, Babson Park, MA, USA
e-mail: wjglover@babson.edu

R. Hendricks-Sturrup
Duke-Margolis Center for Health Policy, Washington, DC, USA
e-mail: rachele.hendricks.sturrup@duke.edu

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integrating ethics and equity-centred perspectives into design, recognising system boundaries, developing augmented system design criteria, managing trade-offs and conflicting values, and educating systems designers. Then, we continue our multilevel approach to explore how these might apply to a particular engineering system, systems of health. Finally, based on the key themes and our application of those themes to systems of health, we identify areas for future research.

Keywords

Engineering systems · Engineering systems design · Equity · Ethics · Health systems · Socio-technical systems design

Introduction

Deeper understandings of ethics and equity-centred design perspectives are critical for the advancement of engineering systems design practice and research. The field of engineering ethics "largely developed during the second half of the twentieth century in response to increasing concern about the dangers of technology" (Johnson and Wetmore 2007, p. 568). Ethics within engineering systems design is unique from other small-scale engineering systems because failures can occur even if no one is unethical at the individual level (Newberry 2010). The characteristics of engineering systems, namely, their high degree of technical complexity, social intricacy, elaborate processes, and their aim to fulfil important functions in society, as well as themselves (De Weck et al. 2011), make them highly vulnerable to several ethical dilemmas and inequities that can lead to suboptimal performance.

In the same way that ethics was integrated into mainstream engineering, ethical considerations are becoming more integrated within engineering systems design. However, we find different approaches to including ethics in engineering systems design, leading to some important questions. What ethical considerations or values should be considered in engineering systems design? How do ethical considerations impact varying levels of analysis within engineering systems? How do we raise awareness of ethical considerations and define boundaries for ethical considerations within engineering systems design? How do we manage the large-scale sociotechnical nature and multiple stakeholders that often have disparate interests within engineering systems design (Sussman 2010)? This chapter first highlights the varying ethical considerations within the literature. We highlight equity-centred perspectives including distributive and procedural justice, as well as other ethical values including safety ethics, privacy and trust, autonomy, and sustainability. We explain ethical behaviour at the micro-, meso-, and macro-levels of analysis and describe five major ethical themes present in the current engineering systems design literature: integrating ethics and equity-centred perspectives into design, recognising system boundaries, developing augmented system design criteria, managing trade-offs and conflicting values, and educating systems designers.

Then, we explore how these themes might apply to a particular engineering system, in our case, systems of health. With patients, multiple medical, pharmaceutical, information, and wellness service providers, along with local, state, and federal regulatory bodies, systems of health represent engineering systems with a broad range of stakeholders with differing ethical considerations values (Caicedo 2019). Health ethics experts note the need for the demands of these ethical principles at the patient-provider level in medicine (respect for autonomy, non-maleficence, beneficence, and justice) to not only "apply at the bedside of individual patients but also systematically in the laws and policies of society that govern the access of a population to health care" (McCormick 2018). However, there has been little research to explore how this might be applied in policy and practice. And with raising awareness of health inequities, particularly regarding socio-economic status and ethnicity in the United States, there is great interest to apply equity-centred perspectives to health systems design. Thus, we explore how an engineering systems design perspective might inform more intentional redesign of systems of health for ethical and equitable behaviour. Finally, based on the key themes and our application of those themes to systems of health, we identify areas for future research.

Ethics in Engineering Systems Design

Theories and Ethical Values and Considerations

The ethical approaches within engineering systems design in recent years have become more normative, reflexively exploring and evaluating alternative actions and avenues for change (Johnson and Wetmore 2007). These normative approaches include both deontological and teleogical perspectives (Ruotsalainen and Blobel 2020; Cavanagh et al. 1981; Fiore 2020). Deontological perspectives use rules to distinguish right and wrong and can be related to (a) theories of rights that emphasise the entitlements of individuals and (b) theories of justice that focus on the distributional effects of actions or policies. Deontological perspectives can be considered too rigid compared to teleological perspectives. Teleological or consequentialist perspectives judge actions by their consequences and results. Utilitarian theories, a form of consequentialism, evaluate behaviour in terms of its overall good or well-bring and social consequences, yielding the greatest good for the greatest number of people. Oftentimes utilitarianism can be considered too permissive and may exclude individual rights and justice. From an engineering system design perspective, there tends to be a balance of both schools of thought, with the desire to provide rules while also allowing for flexibility with system outcomes in mind.

Over time, designers have expressed and embedded specific ethical values and considerations within technologies and engineering systems; this is characteristic of an approach called Design for Values. Historically based on value-sensitive design (VSD) that made social and moral values central to the design and development of new technology, Design for Values allows for multiple approaches and theoretical backgrounds. Design for Values also notes that conscious and explicit thinking about the values that are imparted to our systems is morally significant (van de Hoven et al. 2015). So it is important that we review some of the most commonly explored ethical values and considerations within engineering systems design. There are a few ethical frameworks within engineering systems design that prescriptively define multiple ethical values and considerations (e.g., Strenge and Schack 2020). However, most chose to descriptively highlight two to three ethical considerations depending on the needs of their particular setting or system. Specifically, scholars and practitioners most frequently highlight the roles of equity-centred perspectives including distributive justice and procedural justice, as well as safety, privacy and trust, autonomy, and sustainability. We will discuss each of these in turn.

Distributive justice and equity is one of the most commonly addressed ethical considerations in engineering systems design (e.g., Venter and Joubert 2014; Oosterlaken 2015; Sun et al. 2016; Siddiqi and Heydari 2019). Designers aim to assess and minimise the distribution of benefits and costs across an engineering system. For example, Venter and Joubert (2014) compare the cost equity of fuel taxes versus toll road pricing schemes on the 185-km Gauteng Province's Freeway Improvement Project in the Johannesburg-Pretoria area of South Africa. The province has extreme levels of income inequality, so the authors suggest examining the taxation approach through an equity lens as to not overburden the poorest citizens. They found that toll road charging shifted costs toward more commercial vehicles as opposed to fuel taxes that would disproportionately impact private vehicles. Risk distribution is another form of distributive justice and equity. For example, risk equity in hazmat network design can be accessed via the difference in risk between pairs of partitioned zones or placing upper limit/maximum risk on zones (Sun et al. 2016). An equity lens can also be applied to the system's reliability, stability, quality of service, and accessibility (Yeganeh et al. 2018; Siddiqi and Heydari 2019).

Procedural justice examines the consideration of the public's values during design and participation in the design process (Oosterlaken 2015; Strenge and Schack 2020). Including all stakeholders in the design process increases the sense of ownership and control to system users (Mumford 2000; Stahl 2007). For example, while previous approaches to turbine systems design only considered public values upon implementation, the public may be more accepting if they have input as early in the process as possible (Oosterlaken 2015). These practices can also help to alleviate conflicts of interest between users and designer-owners (Tran and Nathan-Roberts 2018).

Another common ethical consideration is safety (Burton et al. 2019; Ruotsalainen and Blobel 2020; Strenge and Schack 2020). Safety ethics consider "the semantic gap, where normal conditions for a complete specification of intended functionality are not present; the responsibility gap, where normal conditions for holding human actors morally responsible for harm are not present; and the liability gap, where normal conditions for securing compensation to victims of harm are not present" (Burton et al. 2019, p. 1). For example, designers of wearables consider overreliance on automated systems as one potential area for ethical concern as the devices may give vulnerable populations such as patients with severe mental health challenges or the elderly a false sense of security or misdiagnosis (Tran and Nathan-Roberts 2018).

Privacy, trust, and autonomy are increasingly major ethical considerations, particularly as artificial intelligence, augmented reality, and virtual reality technologies become more ubiquitous in engineering systems (Strenge and Schack 2020; Ruotsalainen and Blobel 2020; Morris et al. 2020). Data ownership is a common concern, with user data often owned by the company that makes the product or application within the engineering system, and the data is often available for purchase on the consumer market (Tran and Nathan-Roberts 2018). Models are being developed that may support greater trustworthiness for policy makers for the development of autonomous systems (Morris et al. 2020) and for access control within digital health ecosystems (Ruotsalainen and Blobel 2020).

Economic, environmental, and societal sustainability is another commonly explored ethical consideration (Carbone and Sweigart 1976; Sussman et al. 2005). On the one hand, sustainability is increasingly considered one of the required ethical values for any engineering systems design. However, there are still practical applications, e.g., in the case of refrigerants, where environmental sustainability and safety are at odds (van de Poel 2015). Interdisciplinary approaches, including creating teams of engineering systems designers with industrial ecologists, systems scientists, and users, can help to improve the eventual results (Haskins 2006).

Finally, we can also explore poor ethical behaviours in systems, including misreporting (fictitious data), window dressing (taking actions to make data misleading), and “heating the thermometer” (manipulating performance) (Cugueró-Escofet and Rosanas 2017). These poor behaviours are commonly explored in financial systems and are becoming more commonly explored in engineering systems design. For example, in Byron Newberry’s examination of the macro-ethical issues post-Katrina (2010), he found that while individual engineers were rarely responsible for the aforementioned behaviours, it was common for failures such as misuse or exclusion of information to occur at the systems level.

Ethics at the Micro-, Meso-, and Macro-Levels of Analysis

To advance our understanding of how to take a more normative approach to ethics, we find it helpful to also consider ethical considerations, tensions, and behaviours at the micro-, meso-, and macro-levels. Multilevel approaches to description and analysis are in some ways implicit in the way we describe engineering systems. Engineering systems are large scale, complex, and intricate with elaborate processes and include technical, social, managerial, and institutional considerations and infrastructure (Oosterlaken 2015; Ottens et al. 2006; Kroes et al. 2006; De Weck et al. 2011). Examples included water, energy, transportation, communications, autonomous transportation, and military systems that all impact social welfare and human well-being in significant ways (Suchman et al. 2017; Siddiqi and Heydari 2019; Johnson 2020; Ruotsalainen and Blobel 2020). Tangential concepts including large-scale socio-technical systems, enterprise systems, and systems engineering also inform our understanding of ethical behaviour within engineering systems, and at times the terms are used interchangeably. Large-scale socio-technical systems are described as complex systems with intertwined, relational, and mutually influencing social and technological elements (Johnson and Wetmore 2007; Selbst et al. 2019; Siddiqi and Heydari 2019; Johnson 2020). Enterprise systems include the information system components as well as the processes, people, and information and knowledge content of the system (Giachetti 2016). Also, systems engineering, which traditionally focuses on smaller-scale technical systems and with a heavy emphasis on the technological system components, has periodically been used to describe larger-scale systems. For example, ecological systems engineering includes the evolutionary, self-modifying, and large-scale characteristics of ecology and can cause diffuse, less tractable externalities of related systems, e.g., irrigation systems (Peterson et al. 1997).

Within engineering systems and its tangential fields lies a multilevel approach for description and analysis of the interactions between system components. Adapted from ecological and ecosystem studies, the scales of micro- (individual level) and macro- (societal level) can be conceptually and analytically bridged by considering the meso, i.e., the organisation (Bergström and Dekker 2014). Micro-, meso-, and macro-models can be used to represent phenomena and their interactions in these large-scale systems (Rouse and Bodner 2013; Rouse et al. 2009).

This hierarchical approach has also helped to describe ethical behaviour within engineering systems ethics, with micro-ethical, meso-ethical, and macro-ethical issues to consider. Traditionally, micro-ethics focuses on the individual engineer and internal relations of the profession and ends to be the focus of most ethical pedagogy (Morrison 2020; Johnson 2020). Meso-ethics focuses on the organisation within which the individual engineer is interacting and includes organisational approvals and cooperation and the social interactions and acceptance or resistance of fellow system developers and users (Davis 2010). Macro-ethics focuses on the collective social responsibility of the engineering profession and the legal, regulatory, and policy issues involving technology (Morrison 2020; Johnson 2020). Both meso-ethics and macro-ethics have gained more attention in the last decade (Morrison 2020; Newberry 2010). When this broad range and scale of ethics is combined with systemic design techniques, the resultant frameworks can provide a more holistic approach to systems design (Fiore 2020). This approach also presents a useful lens by which we can better understand ethical behaviour, key themes in the existing literature, and opportunities for future research and training in the field on what is needed to create a system engineered for health.

Key Themes

We observe five key ethical themes across the micro-, meso-, and macro- levels of the engineering systems design body of knowledge, summarised in Table 1. First, there is increased awareness for integrating ethics and equity-centred perspectives with societal (cultural) and technological systems (Winner 1980; Mumford 2000; Sussman et al. 2005; Johnson and Wetmore 2007; Stahl 2007; John Clarkson 2018). These articles provide the "burning platform" from which future works

Table 1 Summary of key themes from the literature: ethics in engineering system design

Theme number	Author(s)	Theme title	Theme description
1	Winner (1980) Johnson and Wetmore (2007) Sussman et al. (2005) John Clarkson (2018) Oosterlaken (2015) Dekker and Leveson (2015) Johnson (2020) Peterson et al. (1997) (Tran and Nathan-Roberts 2018)	Integrating ethics and equity-centred perspectives into design	Increased awareness for integrating ethics and equity-centred perspectives into engineering systems design, including societal (cultural) and technological sub-systems
2	Kroes et al. (2006) Fiore (2020)	Recognising system boundaries	Engineering system boundaries influence the inclusion of non-technical elements (social, political, economic, and institutional) and with ethical implications
3	Siddiqi and Heydari (2019) Burton et al. (2019) Ruotsalainen and Blobel (2020), Newberry (2010) Yeganeh et al. (2018) Venter and Joubert (2014) Sun et al. (2016) Carbone and Sweigart (1976) Suchman et al. (2017)	Developing augmented system design criteria	There are gaps in augmented engineering systems design criteria that could include measurable ways to assess and build equity and fairness, access, cost sharing and risk distribution, safety, privacy and trust models, and macro-ethical issues
4	Van de Poel (2015) Oosterlaken (2015) Strenge and Schack (2020)	Managing trade-offs and conflicting values	Managing trade-offs and conflicting values in systems design, including how to account for various stakeholder values in design, with ethically relevant criteria during agile system design
5	Gorman et al. (2000) Fleischmann et al. (2009) Morrison (2020)	Educating systems designers	Educating current and future engineering systems designers and ethicists

have then operationalised ethical consideration in engineering systems design. The classic work of Winner (1980) warns that the need to maintain these crucial systems should “not eclipse other sorts of moral and political reasoning”. Johnson and Wetmore (2007) find that engineering ethicists benefit from the meso- and macro-level, large-scale socio-technical systems view as it allows for a broader perspective for ethical considerations. And over time it appears that scholars and practitioners have looked further and further upstream from implementation and maintenance to identify earlier opportunities for ethical considerations in engineering systems design. For example, Sussman et al. (2005) suggests that ethical considerations should be made as design strategies for implementation. Oosterlaken (2015) later extends that scope to also include ethical considerations within the technological component design itself. Multi-stakeholder participation in decision-making, in particular regarding the design and use of technology, has been linked to greater employee satisfaction and higher productivity (Stahl 2007). And the early articulation of ethical considerations in the design and development process while they can still make a difference is a cornerstone of the Design for Values approach (van de Hoven et al. 2015). This may have interesting implications for the redesign of legacy systems, suggesting that engineering system designers may need to bring novel approaches to consider ethics in areas that have not been subject to prior ethical considerations. Increased awareness of ethics within engineering systems design has included industry-specific applications including healthcare (Dekker and Leveson 2015), autonomous systems (Johnson 2020; Morris et al. 2020), and ecology (Peterson et al. 1997).

Second, there are macro-level considerations to how engineering system boundaries influence the inclusion of non-technical elements (social, political, economic, and institutional) and of the ethical implications of those boundaries (Kroes et al. 2006). Through boundaries, the roles of agents are clarified as being redesigners from the vantage point of being inside the system, making the idea of “total design control” “problematic” (Kroes et al. 2006). This “design from within” conceptualisation is echoed in other institutional perspectives, not solely as a problematic issue, but rather as a new lens by which we can understand value definition, multiple value logics, and how technologies evolve (Kaplan and Murray 2010).

Third, micro-, meso-, and macro-level gaps in engineering systems design criteria have been identified and addressed to include equity and fairness (Siddiqi and Heydari 2019), access (Yeganeh et al. 2018), cost sharing (Venter and Joubert 2014; Sun et al. 2016; Newberry 2010; Carbone and Sweigart 1976; Oosterlaken 2015), and risk distribution, semantic, responsibility, and liability gaps related to safety (Burton et al. 2019), privacy, and trust models (Ruotsalainen and Blobel 2020) and macro-ethical issues (Newberry 2010). This theme is very promising as it takes a more normative approach to ethics to provide more explicit guidance to designers. It also gives a glimpse into what more quantitative systems studies may consider in the future by laying a framework for measurement. For example, Siddiqi and Heydari (2019) explore three equity measures that can become more standard practice for engineering systems design: the Gini Index for measuring income inequality in a population, entropy measures as indices for diversity and inequality, and variation statistics to be applied spatially or demographically. By examining engineering systems design through the lens of ethical gap identification, we can also observe how unanticipated failure modes, design assumptions, competing interests, information, time, and system resiliency all benefit from ethical consideration (Newberry 2010).

In the fourth theme, we explore how to manage trade-offs and value conflict in design (van de Poel 2015), including how to account for various stakeholder values in design (Oosterlaken 2015), ethically relevant criteria during flexible, agile system design (Strenge and Schack 2020). Most approaches are rooted in value-sensitive design (VSD), where conceptual, empirical, and technical investigations are used to consider trade-offs between values such as privacy, physical welfare, usability, and trust (Friedman et al. 2001). One model by Fiore (2020) combines VSD with professional ethics approaches from information systems to take an applied ethics approach to Internet of Things (IoT) and artificial intelligence (AI) systems. Strenge and Schack (2020) acknowledge the role of VSD, but also recognise the limitations of stakeholders' ability to recognise values, harms, and benefits in advance. Instead, they root their trade-off approach in agile methodology, allowing designers along with other stakeholders to regularly readjust the development process. This model may be ideal in increasing procedural justice, but may be challenging when redesigning within legacy systems. Within the Design for Values approach, van de Poel (2015) recommends a step-wise approach to reconciling potentially conflicting values; he combines satisficing with moral obligations, innovation, and then choice. The inclusion of innovation is particularly helpful here in order to help designers "ideate" beyond their perceived trade-offs when possible.

Lastly, the literature encourages educators of engineering professionals and engineering systems designers to integrate ethics into college and professional curricula (Cutler 1992). Cases can be framed to discuss such ethical dilemmas as individual and geographic diversity in decision-making, considering multiple perspectives, understanding one's own values and considering the values of others, and considering a pluralistic view of "right and wrong" (Fleischmann et al. 2009). Cases aim to engage the "moral imagination", encouraging students to recognise their own values and perspectives, disengage from them, and evaluate alternative perspectives and courses of action (Gorman et al. 2000). There is a long tradition of teaching ethics in the context of major disasters; more recently, new techniques such as postphenomenology has been used to teach engineering ethics by combining the standpoint of lived, everyday experience with the data of social scientific accounts of technical objects and systems (Morrison 2020) (Table 1).

Examining the Role of Ethics at Key Levels Within a System Engineered for Health

We now apply the insights from the aforementioned ethical considerations, levels of analysis, and our five key themes to an illustrative case industry: systems of health largely in the United States. Health is a particularly timely area for exploring ethics in engineering systems design, in part due to the timing of this publication during the

COVID-19 crisis. This pandemic has emphasised the extreme inequities in health systems design, particularly in the United States, and the need for ethical frameworks to guide redesign efforts in the coming years. By applying our levels of analysis and major themes from the engineering systems design ethics literature to health, we can observe the degree to which we can apply findings from highly technical systems to more human and service-centric socio-technical systems. With the emergent properties inherent to socio-technical systems, we are not prescribing specific components or activities for ethical consideration. Rather, our goal is to inspire the careful and thoughtful development of ethical guiding principles for future designers to think about ethical considerations in these types of systems.

Systems perspectives are often applied to health and healthcare at the micro-, meso-, and macro-levels. At the micro-level, systems perspectives and Design for Values have been applied to several technologies. Design for Values has been applied to extend our thinking of assessing healthcare technologies. Previously, health technologies were primarily assessed from the perspective of the costs compared to the health gains. More recently, health technologies are being assessed based on the potential for that technology to express human values, e.g., cochlear implants for deaf children (Van der Wilt et al. 2015). Systems design for evolvability, or designing for more manageable transitions between current and future system designs, has also been explored for MRI systems and Point-of-Care in vitro diagnostics solutions (Patou and Maier 2017).

At the meso-level, systems perspectives are most commonly expressed through complex adaptive systems theory. The complexity of care has skyrocketed, with more clinical prevention, diagnoses, and treatment options, increased interdisciplinary care, and more interconnected stakeholders, calling for complexity science and complex adaptive systems (Plsek and Greenhalgh 2001). Complex adaptive systems theory considers the non-linear, dynamic nature of system behaviours coupled with intelligent agents that can result in self-organisation and no single point of control (Rouse 2008). We have used complex adaptive systems theory to explore how innovation occurs in hospital systems (Glover et al. 2020); in that study, we found that the dynamic role of clinicians as agents, via a balance of autonomy and direction, significantly influences innovation; the importance of agent autonomy represents a significant, human-centric factor, highlighting the importance of a socio-technical systems view of health systems. Also, the inclusion of patients and staff as agents in the design process of new health systems may result in greater innovation in the development and implementation of new health solutions (Smetana and Larsen 2020).

Systems perspectives have also been used to explore the intersection between large health organisations and policy at the macro-level. For example, we have used enterprise systems architecting to identify areas of opportunity for improved psychological health policy for the US Military Health System via multiple lenses including ecosystem, stakeholders, strategy, process, organisation, knowledge, information, and infrastructure (Glover et al. 2015). Also, systems studies of population health, i.e., the integration of health, education, and social services to maintain a healthy population, have found that multiple levels of abstraction and modelling are needed to examine and understand the broad scope of forces that affect the health of a population (Rouse 2021).

Collectively, systems perspectives note that multiple components, lenses, and representations are often needed to describe systems of health. We carry this principle into our discussion of ethics in systems of health via an engineering system design perspective.

Micro-, Meso-, and Macro-Ethical Considerations in Health

Ethical standards or codes exist at the micro-, meso-, and macro-levels within a system of health (see Fig. 1).

At the most basic or micro-level (one-to-one patient-provider level), key long-standing ethical principles in medicine are beneficence, non-maleficence, justice, and respect for autonomy (Sulmasy and Bledsoe 2019; see Fig. 1). Over 25 years ago, Gillon (1994) suggested concern for or "attention to scope" as another guiding principle, and thus we draw on "attention to scope" in the sense that these four long-standing ethical principles in medicine inform or set the foundation for ethics at the higher meso-level, which are organisations and institutions where patient-provider interactions occur.

At the meso-level, there are professional ethical principles and codes to which professionals are expected to endorse or adhere as they engage among themselves as peers serving a common stakeholder population and function within and with stakeholders serving the interests of the broader macro-level system. For example, professional engineers are expected to adhere to professional standards and codes in

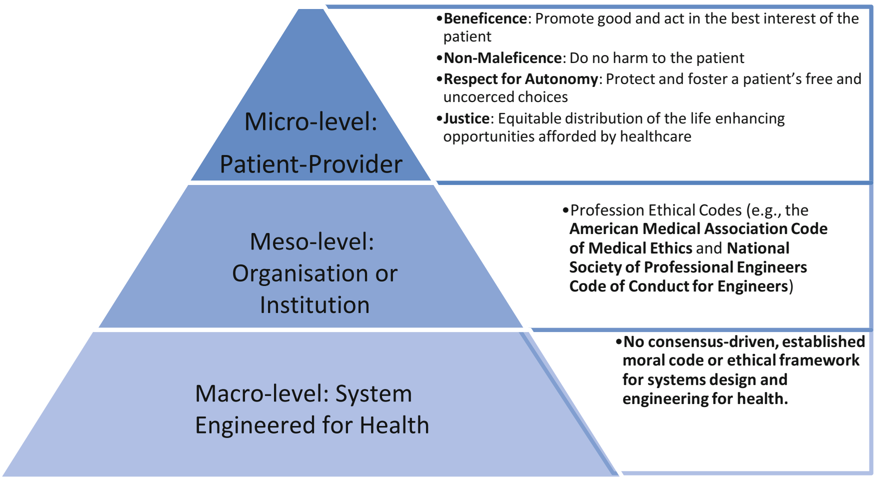

Fig. 1 Overview of ethical standards at micro-, meso-, and macro-levels in a system engineered for health

engineering ethics to protect themselves and others within the community as they perform their professional duties. Specifically, the National Society of Professional Engineers (2020) Code of Conduct for Engineers offers as one of its "fundamental canons" (in Part I) to "*hold paramount the safety, health, and welfare of the public*". The Institute of Electrical and Electronics Engineers' (IEEE) Code of Ethics offers similar yet more encompassing guidance (in Part I): "hold paramount the safety, health, and welfare of the public, to strive to comply with ethical design and sustainable development practices, to protect the privacy of others, and to disclose promptly factors that might endanger the public or the environment" (IEEE 2013).

In addition, the American Medical Association (AMA) Code of Medical Ethics contains 11 chapters enshrining professional codes of conduct grounded on the basic principles of medical ethics (covered in the micro-level discussed in Fig. 1) to ethics regarding health care financing and delivery (American Medical Association 2020). Like the AMA Code of Ethics, the American College of Healthcare Executives (ACHE 2017) Code of Ethics contains six sections enshrining codes of conduct. Although unlike the AMA Code, the ACHE Code appears more specialised or targeted to healthcare executives who may or may not be healthcare providers. Perhaps most notable and relevant to this discussion, both the AMA and ACHE Codes contain sections that embody the spirit of engineering systems design for health and could thus naturally inform the development of ethical codes and principles at the macro-level noted in Fig. 1. These sections focus on the community as a living, functioning, dynamic, and largely influential system for health. The AMA summarises their guidance in Chap. 8, entitled "Ethics for Physicians & the Health of the Community", as "a doctor's job doesn't stop at individual care. Find out how *caring for the health of the community* can also lead to better health for individual patients". In section 5 of the ACHE Code of Ethics entitled "The Healthcare Executive's Responsibilities to Community and Society", the healthcare executive's "responsibilities to community and society" are summarised, in part below, as embodying a very similar scope:

- "Work to identify and *meet the healthcare needs of the community*;
- Work to identify and seek opportunities to foster *health promotion in the community*;
- Work to support *access to healthcare services* for all people;
- Encourage and participate in *public dialogue on healthcare policy issues, and advocate solutions* that will improve health status and promote quality healthcare;
- Apply short- and long-term assessments to management decisions *affecting both community and society*; and

The macro- or system-level of health, as we offer in definition, is the culmination or entirety of a network of people, institutions, and resources that provide services and perform functions that impact social determinants of health for a targeted community or region. Social determinants of health are economic stability, neighborhood and physical environment, education, food, community and social context, and healthcare delivery organisations (Artiga and Hinton 2018). While the literature provides commentary, recommendations, and discussions on ethics in engineering systems for health (Fabri 2008; Schröder-Bäck et al. 2014), there is scant evidence of expert stakeholder-driven consensus on a moral code or set of ethical principles for engineering systems design for health. Fabri (2008) suggested that, "fixing health care will require individuals who are "bilingual" in health care and in systems engineering". We concur yet challenge healthcare and engineering systems expert stakeholders to continue collaborating on the development of a consensus-driven code or framework of key ethical principles that will inform the redesign or development of socio-technical systems designed or engineered for health. We offer these ethical principles and codes as key ethical foundations and draw on the five key themes from the literature for consideration that capture elements of distributive justice and equity, safety, procedural justice, privacy and trust, and sustainability.

Ethical Themes Applied to Health

So far, we have discussed important ethical principles and codes that exist at micro-, meso-, and macro-levels and that could thus be transformed or applied within the scope of systems that influence or control population health. In this section, we describe, through an assessment of case scenarios or examples, negative consequences that have ensued or may ensue in the present day should there be ethical tension or inattention across these three levels. We do so through our five themes: integrating ethics and equity-centred perspectives into design, recognising system boundaries, developing augment system design criteria, managing trade-offs and conflicting values, and educating systems designers.

Theme 1: Integrating Ethics and Equity-Centred Perspectives into Design

Theme 1 of our literature review findings centres on increased awareness for integrating ethics and equity-centred perspectives into engineering systems design, including societal (cultural) and technological sub-systems. In the same way that the engineering field has, as a whole, shifted from ethical awareness of the individual engineer to systems-level ethical awareness, we observe a dearth of evidence of guiding ethical principles to support the collaboration between health system stakeholders and engineers who are tasked with building key infrastructure to support and sustain systems for health. Moreover, moving into the twenty-first century, an era in which data has and will increasingly be used to support individual and organisational decision-making, critical engineering infrastructure is now both structural and digital. The rapid and continuous advent and implementation of new technological sub-systems, integration of powerful data collection and management systems, and broadening influence of non-traditional health companies providing health-related services to patient-consumers create opportunities for greater ethical awareness, particularly at the meso- and macro-levels.

For example, the equity-centred perspective of "justice" at the micro-level needs to be reconsidered at the meso-level to be engineered for a heterogeneous population (e.g., urban/suburban populations *and* rural constituents) and with a clear understanding of the patient journey within an engineered system. Without such consideration, there may be a sufficient quality of patient-provider dynamics, but poor quality of system-level dynamics, trust, and/or outcomes once the patient exits the micro-level setting. In addition, powerful industries that partner with health systems to provide data management or communication support infrastructure may hold profit motives that to not reflect awareness of the principles of "beneficence" and "respect for autonomy", particularly if the industries' privacy policies appear coercive and erode patient confidence and trust.

History tells us that when ethical principles, standards, or codes are not present across all levels, unethical behaviour may arise. One widely publicised example is the Tuskegee Study of Untreated Syphilis in the Negro Male conducted between 1932 and 1972 by the United States Public Health Service in Macon County, Alabama (Centers for Disease Control and Prevention 2019). The Public Health Service partnered with the Tuskegee Institute to examine the long-term effects of syphilis infection in 600 Black men, 399 of which were diagnosed with syphilis. Several ethical issues were found in this study at the micro-, meso-, and macro-levels, yet the study alarmingly lasted for 40 years. First, the participants enrolled did not give informed consent, as they were misled by the researchers and clinicians to believe they suffered from "bad blood" versus syphilis infection. Second, although syphilis treatment was widely available, and the 399 patients were formally diagnosed with the condition upon or during enrolment in the study, treatment was withheld from those patients for observational research purposes. This resulted in medical malpractice, negligence, and immediate and long-term harm to the infected patients. Lastly, it is often the case that these sorts of ethical conflicts or issues become exposed when their stories or findings are shared at the meso-level, perhaps when it is too late in terms of irreparable harm being done. This is especially true for macro-systems built on antiquated or even biased ideologies, cultures, assumptions, and beliefs (Caicedo 2019). In the 1932 Tuskegee study, it was only after a major paper had been published showing the study results that the study ethics were challenged and criticised, as the authors of the paper did not reveal if the men were actually being treated. What is most alarming in this case is that local physicians within the community complied with the Tuskegee Institute's request to not treat the infected men so as to not interfere with their observational study aims. Therefore, in this case, the lack of meso-level ethical behaviour within this system supplanted or superseded the ethical behaviour that was expected at the micro-level.

Another ethical concern, yet perhaps mainly at the micro- and meso-levels regarding informed consent like the Tuskegee study, is that randomised clinical trials today run the risk of exploiting emergency or acute health situations among marginalised patients. Take, for example, ethical tensions that are inherent to the informed consent process for randomised clinical trials involving emergency obstetric care (Kaye et al. 2019). Obtaining informed consent in such situations can be morally and practically challenging for researchers with regard to upholding the autonomy and welfare of both the expectant patient and foetus and navigating sensitivities and vulnerabilities that accompany such situations, which are often compounded by the severity of the patient's disease, powerlessness, or impaired decisional capacity. It is also true for this scenario that meso-level ethical behaviour within this system could thus supplant or supersede the ethical behaviour that is expected at the micro-level between a doctor and patient.

In such cases, expectant or delivering patients and their caretakers must not only consider the function and availability of emergency obstetric services, service providers, and infrastructure available to them in extreme or emergency circumstances; they must also navigate cultural and structural biases that might be embedded structurally within the systems in which they seek care. In the United States, African American women bear the highest risk and rate of maternal mortality due to, as research suggests, societal factors like structural racism and implicit bias. If an expectant patient must seek emergency obstetrical care within a system of health that was built or culturally based on disregard for the autonomy and beneficence of African Americans, then therein lies the key ethical tension. In this emergency or acute health situations where randomisation into a clinical trial is possible, there is risk of African American patient exploitation. This is especially true if the patient's decisional capacity is impaired and if broader social dynamics and biases are potent enough in that structural setting to render the patient powerless and thus at risk of harm or maleficence.

Earlier stage user inclusion from more diverse patient and patient caregiver groups could be implemented to increase ethical consideration during the early stages of design for health systems. For example, research and engagement grant-making institutions in the United States, like the Patient-Centered Outcomes Research Institute (PCORI), require patient and patient caregiver groups to be involved during research design. A similar approach could become standard within healthcare process improvement, healthcare industrial and systems engineering, and health redesign communities. Also, a joint effort between the National Academy of Engineers and the Institute of Medicine including a diverse set of experts to focus solely on ethics within engineering systems design for health, similar to previous efforts integrating engineering and health (Reid et al. 2005), would greatly support the development of shared ethical language, standards, and practices across the two disciplines.

Theme 2: Recognising System Boundaries

Theme 2 of our literature review findings centres on the notion that engineering system boundaries influence the inclusion of non-technical elements (social, political, economic, and institutional) and have ethical implications. From an agnostic or general engineering perspective, we define or describe such boundaries as physical or administrative elements or components within a system that hold a purpose to create "safe spaces" that are required for specific activities or transactions to occur. Non-technical elements that have political or social undertones, and thus potential ethical repercussions or tensions for creating, eliminating, or reinforcing such boundaries, are often considered on a case-by-case basis.

For example, in the NSPE Ethics Reference Guide (2020), there are several case examples illustrating the importance of systems boundaries. For example, in the "Conflict of Interest—Engineer Serving on Private Hospital Board and Performing

Services" case example, a principal engineer at a firm conducted research to confirm that a reclaimed commercial waste dump site contained hazardous chemicals that could surface over time and that site was not shut down in accordance with the hazardous and solid waste regulations of the state. The city in which the dump site was located considered plans to build several recreation spaces and a parkway near the reclaimed area. In addition, a river near the reclaimed area was used for drinking water by nearby localities. When city officials received the engineer's initial research findings, the city decided to move the recreational development to another site in an abundance of caution to avoid political ramifications of revealing the engineer's findings and to avoid financial responsibility for the site cleanup. Also, the engineer was bound by a legal confidentiality clause that would prohibit the engineer from going public with the confidential research findings.

In this NSPE case study, the city withdrew its position to build a recreational space near the polluted site only for political and financial reasons, but not for reasons that would align with ethical principles. Had the city and engineer been held to a professional ethical standard and thus obligation to notify public health authorities about the hazardous waste site, public health authorities would have been able to notify local healthcare providers become vigilant for any signs of chemical poisoning within the community. This would create a broader set of non-technical elements to consider (social, political, economic, and institutional) and would broaden the engineering system boundaries from project-centric to public health centric. It would be at this very point in which micro-level ethical principles have become interoperable with principles at the meso- and macro-levels to create a system engineered for health.

Future research and practice should consider the role of broader system boundaries, shifting the focus from what can and can't be "controlled" to what and who can positively be informed. One way to accomplish this goal, within the system of health scope, would be to identify and examine how certain boundaries that are either set or being built within the system influence the inclusion or exclusion of, for example:

- Local small businesses or establishments
- Historically disenfranchised populations or groups
- Groups or individuals who have experienced some level of social or domestic abuse
- Populations or groups at highest risk of misdiagnosis
- Individuals or groups seeking to protect or uphold their personal or health information privacy
- Individuals without safe and reliable transportation
- Individuals with physical or mental disabilities

It is also important to question, when considering these factors in building or recreating a system engineered for health, how the traditional ethical principles in medicine (beneficence, non-maleficence, justice, and respect for autonomy) might also serve as an ethical foundation for this engineering process. Special attention and consideration to such details upfront are key to the development of a consensus-driven moral code or ethical guide at the system-level.

Theme 3: Developing Augmented System Design Criteria

Theme 3 of our literature review findings describes that there are gaps in engineering systems design criteria that could be augmented to include measurable ways to assess and build equity and fairness, access, cost sharing and risk distribution, safety, privacy and trust models, and macro-ethical issues. This particular theme moves beyond the more foundational aspects of designing a system for health in Theme 2 to more technical aspects of ethics in design criteria. This would augment, for example, current engineering systems design criteria or code specifications with ethical underpinnings, such as criteria to accommodate physically disabled persons in both public and private settings or limit the level of hazardous waste disposal in public water sources. Filling such gaps in engineering systems design criteria also opens opportunities to build and apply new measurable systems design specifications (e.g., specifications on access, cost sharing and risk distribution, safety, privacy, etc.) grounded in the traditional ethical tenets in medicine (beneficence, non-maleficence, justice, and respect for autonomy).

These same considerations can be applied at the meso-level, which is the very structural element in which interactions and other social phenomena occur at the micro-level. The NSPE Code of Ethics for Engineers highlights, in their preamble, that engineering “has a direct and vital impact on the quality of life for all people. Accordingly, the services provided by engineers require honesty, impartiality, fairness, and equity, and must be dedicated to the protection of the public health, safety, and welfare”. This notion directly embodies the spirit of Theme 3, thus lending encouragement to those seeking to find nexus or alignment between established ethical principles at the meso-level and developments the engineering systems design literature.

Moreover, Herkert (2004), who also elucidated micro- versus macro-level ethical issues in engineering practice in a National Academies report, stated that professional societies “could potentially serve as a conduit to bring together the entire continuum of ethical frameworks by linking individual and professional ethics and linking professional and social ethics”. Herkert further stated that in “the domain of macro-ethics, professional societies can provide a link between the social responsibilities of the profession and societal decisions about technology by issuing position statements on public policy issues”. Thus, Herkert’s conclusions and recommendation resonate and align with those of our own.

Theme 4: Managing Trade-Offs and Value Conflict in Design

The idea of using systems engineering design as a tool to influence population health outcomes and overall well-being today and for generations to come can engender inspiration. However, when opportunities arise to execute the idea and implement new or redesign existing systems, several system underpinnings and limitations are often revealed. This may be one of the most promising, fruitful areas for future research, with many areas of tension to address. First, tensions arise among powerful health system stakeholders who might arbitrarily apply dichotomous reasoning in their attempts to resolve conflicts or disputes (Pater 2005; Silva and Ordúñez 2014). The consequences of addressing causality as dichotomous or attributable to isolated agents, not as the result of a multifactorial process that gradually develops, have been problematic in previous population health studies of tobacco and global warming (Silva and Ordúñez 2014). In taking an engineering system design approach to ethical behaviour, we would suggest the practice of procedural justice to consider multiple perspectives and increasing ethical awareness to mitigate dichotomous reasoning. For example, policy flight simulators using multiple representations and involving multiple stakeholders may be one approach to shift from dichotomous to more synergistic problem solving (Rouse 2021). Patient-centricity and community goodwill foci that are agile approaches to value-sensitive design and that include community members early on in the design process may also help to mitigate dichotomous reasoning.

The system of health also faces seeming differences in ethical behaviours, choices, and concerns among key system stakeholders for various legitimate reasons as well, e.g., scarcity of resources, patient autonomy, protecting system workers, and data sharing (Mbuthia et al. 2019; Kopar et al. 2020). Tensions and imbalance can particularly arise from the perspective of less powerful stakeholders functioning within changing health markets and market cultures (Azguridien and Delkeskamp-Hayes 2015; Viana and da Silva 2018). To mitigate this tension, value-sensitive design-based approaches may be ideal, but, to date, have only been applied at the micro- or meso-levels of the system of health. For example, at the micro-level, van Wynsberghe (2013) explored value-sensitive design for care robots. At the meso-level, Walton and DeRenzi (2009) applied value-sensitive design to develop and implement health information systems in rural areas in sub-Saharan Africa and have explored ethical awareness of big data in Swiss healthcare systems (Dorey et al. 2018). To date, frameworks at the national systems level have suggested that health systems must choose its dominant value, for example, a system may choose to focus on a utilitarian efficiency and thus disregard equity for underserved populations (Atun et al. 2013). This presents great opportunity to develop and apply ethical engineering systems design frameworks at the macro-level for systems of health that are more flexible to account for multiple values. We might expect most of the tension to occur between patients and payers, but with the patient-centred care movement well underway at the micro- and meso-levels, we may be at a unique point in history, particularly in the United States to apply a large-scale ethical approach not only to policy, but to specifications and exemptions in design.

Ethical tensions can also arise from the legacy systems that comprise the engineering system; as new technological components emerge, designers must consider the extent to which are in harmony or discordant with the ethical behaviours established by the existing system (De Weck et al. 2011). Systems of health are heavily influenced by their structural and political origins, causing ethical tensions as new technical capabilities emerge and are introduced into the system (e.g., innovation, precision medicine, and AI). For example, when the World Bank introduced a new funding platform, its implementation was delayed 3 years, in part because of untested assumptions including partners' desire to adopt the World Bank's application, funding, and evaluation procedures. Scholars suggest not only testing such assumptions but revisiting legacy values that serve as the foundation for how such changes are made, including political and bureaucratic convenience (Brown et al. 2013).

While traditionally, engineering systems design scholars have been pessimistic about the ability to change engineering systems due to legacy ties, an ethical lens may allow designers to disconnect from legacy systems via the creation of new systems. For example, in the United States, there are new in-home primary care services targeting underserved populations that are not connected to any major existing health system and are developing more equitable payment systems. In other cases, portions of legacy systems are still accessed, but in new ways. For example, in low- and middle-income countries, electronic health records are often designed via open-sourced platforms that allows for more customised, flexible, and user-friendly resultant data to inform decisions. This also illustrates ethical design through affordability and equity. This also presents an opportunity for future research to explore the ways in which ethics may lead to rethink or dispose of legacy systems for a more ethical future.

Theme 5: Educating Current and Future Engineering Systems Designers and Ethicists in Health

From both the National Academy of Engineers and the National Institutes of Medicine, there have been joint efforts to take a more interdisciplinary view of health and to suggest that more macro-ethical frameworks and methods are needed (Herkert 2004; Reid et al. 2005). Perhaps the most applicable take away from the general engineering systems literature, as it would apply to systems of health, is the importance of examining "everyday experiences" of humans navigating the system, like patient and caregivers. Places in curricula that may easily be adjusted to include ethical engineering systems design discussions would be design thinking and process analysis, design thinking within operations management courses, structural competence content within public health and health equity courses, computer and data infrastructure engineering, and during human systems integration content within systems engineering courses.

Conclusions

Given the importance of ethics within engineering systems and with the premise that engineering systems can be explicitly designed and adapted with ethical behaviour in mind, we seek to make four contributions to the engineering systems design literature. First, we provide a summary of the definitions of ethical values and considerations within the context of engineering systems design. We find that roles of distributive justice and equity, safety ethics, procedural justice, privacy and trust, autonomy, and sustainability are commonly explored in the engineering systems design literature. Second, we describe the importance of a multilevel approach in order to develop and implement designs that account for those ethical considerations at the micro-, meso-, and macro-levels of analysis. Third, we identify five key themes in the literature: increasing awareness of integrating ethics and equity-centred perspectives into engineering systems design, the influence of engineering system boundaries, engineering systems design criteria to include measurable ways to assess equity, managing trade-offs and value conflict in design, and educating current and future engineering systems designers and ethicists. Fourth, we present the system of health as a case, exploring how the literature describing this particular engineering system converges or diverges from the ethical considerations within the engineering systems design body of knowledge.

Overall, we find that ethics can be a valuable lens not only to improve the moral compass of design, but to make design more effective and appealing to all involved stakeholders through more early-stage inclusive design. Our application to systems of health highlights the importance of a multilevel view and why having the Hippocratic Oath on the micro-level does not guarantee macro-ethical behaviours. This literature review highlights many areas for future research. For example, we presented a representative review of the ethics in engineering systems design literature. Future research could consider a full systematic review or co-citation analysis to explore the relationships between the multiple disciplines involved in this area of study. We found several ethical considerations within the body of knowledge; future research could explore the relationships between them and provide more quantitative measurement tools for assessing each ethical dimension. Finally, future research should consider the application of value-sensitive design and other engineering systems design tools that can address ethical tensions within less explored engineering systems, such as systems of health. By applying these tools to these new areas, we may find new pathways for developed shared language, appreciation, and understanding for differing ethical values across stakeholders.

Cross-References

▶ Designing for Emergent Safety in Engineering Systems
▶ Engineering Systems Interventions in Practice: Cases from Healthcare and Transport
▶ Roles and Skills of Engineering Systems Designers
▶ Sustainable Futures from an Engineering Systems Perspective
▶ Technical and Social Complexity
▶ Transitioning to Sustainable Engineering Systems

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Roles and Skills of Engineering Systems Designers

30

Panos Y. Papalambros

Contents

Abstract

There is increased recognition that modern engineering systems design integrates the complementary nature of classical design thinking and systems engineering thinking. Engineering systems design must consider not just the artefact but also its associated services, the ecosystem and supply chains necessary for its creation and operation, the communities where it is produced and operated, its relation to government regulations and policy, its impact on the environment, and its long-term influence on social behaviours. Whether the artefact is an airplane or mobile phone, systems designers must address these multifaceted society expectations balancing them with the inevitable associated risks and unintended consequences. What does this mean for engineering systems designers, their evolving role in large design organisations and the attendant skills they need? What are these skills and how do they get acquired? This chapter addresses these questions by reviewing the roles and skills of engineering systems designers, exploring the

P. Y. Papalambros (✉)
Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI, USA
e-mail: pyp@umich.edu

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organisational and social motivations behind this evolution in thinking, and discussing the implications for individual designers. We introduce the concept of two types of engineering systems designers: *Type* 1 is an engineer technically responsible for the overall design, performing conceptual design, architecting the design, and superviings the work of the organisation during detailed design, integration, and testing. *Type* 2 is an engineer responsible for embodiment design, integration, and testing. Individual designers may have elements of both types in their jobs, but the skills associated with each type are quite distinct, and a short discussion on such skills acquisition is included.

Keywords

Design thinking · Education · Engineering systems · Roles · Skills · Systems design thinking · Systems thinking

Introduction

Design is the human activity that creates and embeds artefacts in our world. Humans have been modifying the world through design since their very early days. A system is a collection of entities that perform a specified set of tasks (Papalambros and Wilde 2017). In the broad dictionary definition, a product is something composed, created, or brought out by intellectual or physical effort (Merriam-Webster 2019). Artefacts are human products. More narrowly, a product is something sold by an enterprise to its customers (Ulrich and Eppinger 2017). Traditionally product design has been associated with common "consumer" products, while systems design has been associated with "complex" products such as aerospace transportation vehicles or energy generation plants. Design thinking reflects cognitive and other processes preoccupied with understanding the product user; systems thinking reflects preoccupation with artefact complexity. Today, engineering systems designers employ these two modes of thinking in a synergistic and complementary manner.

Any modern artefact, even the simplest one, can be viewed as a system, if one considers the details of its parts, materials, production processes, supply chains, distribution channels, expected and unexpected uses, impact on the environment, impact on users and non-users, and end-of-life retirement. As the distinction between product and system has blurred, so has the distinction between design thinking and systems thinking. As a result, the roles and skills of systems designers have evolved to align with this realisation.

In this chapter, we review how the concept of the engineering systems designer evolved from the mid-twentieth century to now, the present needs in engineering systems design, and the concept of *systems design thinking* as the blending of previously separated cognitive processes. We introduce two types of systems designers: *Type 1* deals with overall design, performing conceptual design, partitioning (architecting) the system, and supervising the organisation's work during detailed design, integration, and testing; *Type* 2 deals with embodiment design, integration, and testing and coordinating design teams that work on subsystem/component design. We then discuss what are the roles of today's engineering systems designers and elaborate on the two systems designer types we identified and the skills needed to execute them.

The Engineering Systems Designer of the Twentieth Century

Systems design emerged as a discipline in its own right in the mid-twentieth century primarily in the USA. One reason was the need for designing the operations of systems like transportation and delivery of supplies during war time, an activity that was eventually called operations research (and more recently mathematical optimization). The work needed in this type of design was mathematical modelling of the operations as optimisation problems and methods for solving robustly the resulting models. System complexity was primarily due to high dimensionality (e.g., thousands to millions of variables), non-linearity, mixed discreteness, and other such mathematical adversities along with computational cost. Another reason was the need for designing aerospace vehicles by hundreds or thousands of engineers, comprising a very large number of tightly interacting parts and where even one system failure was not acceptable. System complexity was primarily due to the interconnectivity of parts and the need for the resulting system to meet mission specifications with extremely high degree of reliability. This latter type of designing became identified as "complex engineered systems design" (Bloebaum and McGowan 2010).

The role of a system operations designer has been the development of computational models and solution methods. The requisite skills are in mathematical modelling and numerical methods but with little need for physics-based models because operations models do not typically include the detailed functionality of individual system elements. The role of a systems engineer has been to partition the system into elements (subsystems and components), perform the actual embodiment (detailed) design of the system elements, and integrate all the parts so that the resulting system is consistent and meets the overall mission goals. This task requires deep knowledge of the physical behaviour of the system and its parts and of how such behaviour is affected by design changes and variations in externalities, like the environment where the system operates.

Both operations-based and physics-based engineering skills are necessary for systems design. For example, manufacturing an airplane or automobile requires not just designing the physical system but also its assembly and the supply chain that will provide the parts. System performance decisions are coupled with manufacturing, assembly, and supply chain decisions; this coupling adds another dimension of complexity in systems design requiring both types of the above skills.

Software systems engineering is a particular domain of increased importance and shares the same coupling characteristics (Bourque and Fairley 2014). A software system is often built using the functions of existing codes as building blocks, and so partitioning of the system and coordination of the blocks used is a critical task. Software implementations may be tightly coupled with hardware that must be specifically designed for the particular execution, and therefore physics-based engineering is necessary. Software systems execute operations and so all operations-related considerations, such as efficiency, reliability, and maintenance, are applicable. Many software systems provide a direct service to the user and so the user experience is an important consideration. All of the above tasks are related, and the software systems engineer must have the skills to manage these relationships.

The large number of engineers and other specialties required for systems design implies a need for management of the entire process. Such management typically requires establishing processes for communication and early detection of errors, as well as establishing consistency of the decisions made in different but interacting parts of the system. With systems engineering emerging as a discipline, the role of a systems engineer became twofold, possibly executed by different individuals. One role is to ascertain that communication and interface protocols are properly executed and adhered to by different parts of the organisation. The other role is to provide technical leadership at the *system* level and make the decisions on potentially conflicting needs in different parts of the system. The engineering systems designer emerged as a system integrator and technical leader, roles that may require decades of experience within an organisation.

The nature of the system customer is another important design consideration. In most of the twentieth century, the archetypical complex engineered system was the aerospace vehicle (see, e.g., Hamstra (2019)). This situation continues to the present. For many of these systems, the customer is a single entity, usually a government agency. The agency sets the mission specifications, conducts a bidding process in a transparent manner, and awards the contract based on these specifications. The contractor must deliver the system on time and budget and with the given specifications. The government decides whether the contract was properly executed, including validation of the system. While one can argue that the bidding process brings a market consideration into the process, the single customer situation is far from letting the market decide eventual success. In stark contrast, arguably complex engineering systems like modern automobiles or software are subject to the market forces of a product, and validation comes from the buying public. The difference in customers has profound impact on systems design. For example, while mission specifications generally stay the same for a rocket, performance requirements for an automobile can change dramatically in a short time.

The Twenty-First-Century Needs

The benefits of applying systems engineering to large design projects have been widely recognised. Systems engineering is practiced in many industries and taught in most academic engineering curricula. Still, some voices of caution emerged early on, particularly in the quest for rational, systematic planning of complex projects addressing socio-technical problems using the methods of operations research. A most notable such caution was putting forth the concept of “wicked” problems – problems that are largely impossible to solve because of changing, contradictory, or incomplete requirements (Rittel and Webber 1973). To a large extent, wicked problems owe their presence to the direct involvement of humans in establishing the nature of their requirements.

Wicked problems such as climate change have come to dominate much of the public discourse and anxiety about the future. The belief that technology can solve wicked problems has been deeply shaken in part because technological solutions for one problem have consequences on other aspects of our lives, often unintended but still very real, creating new wicked problems. The need for human involvement, individual or social, in addressing such a problem cascade amplifies the expectation, indeed the demand, from society that engineering systems designers must not only address the problem at hand but also alleviate the creation of new ones, often well into the future. Moreover, we have to address the operation and effects of so-called legacy systems that are already in place such as power generation grids or packaging systems with well-understood unintended consequences. Design interventions for legacy systems rather than new ones are wrought with wicked challenges. Society expects systems designers to address undesired consequences but may be reluctant to accept required behavioural and economic requirements, eventually venturing into political discourse. Thus, systems design in the twenty-first century far exceeds the traditional technical and business considerations and requires a holistic approach with a view long into the future.

Furthermore, in the last two decades or so, systems engineering started receiving closer scrutiny for its use in large government (single customer) projects because such projects seem to be almost always over time and over budget. Government agencies, having spent significant funds already, would be resistant to abandoning a project without a final deliverable, thus forced to extend budgets and timelines. Contractors of the systems design might blame the customer for changing mission requirements in the middle of the design process. In this environment, systems engineering is still highly valued, but there is a clear perception that it is not good enough as practiced (Griffin 2010). Even when accounting for the politics of decision-making in such large projects, the perception of more fundamental issues in the execution of systems engineering remains strong.

A possible explanation of why “classical” systems engineering is not enough follows the same thinking as for the wicked problems. Systems design organisations comprise a community of humans, designers, managers, engineers, and administrators. Therefore, the execution of a systems design project is a socio-technical problem and carries the direct involvement of humans (Flumerfelt et al. 2019). While in the original wicked problems human behaviour was the subject of modelling, in the systems engineering practice we largely ignore the human presence assuming that, for example, the establishment of processes like information protocols and interface documents is sufficient for system integration.

Another point of contention in the execution of systems engineering is the sanctity of mission or top-level system specifications. This sanctity is driven in part by the legal, contractual process for awarding projects by government agencies based on bidding against the stated requirements and costs. This process makes changing the requirements a messy proposition, but change they do due to a changing nature of the need, new technology, or deeper knowledge. These changes carry costs in time and money. The critique, however, is that a design process driven by meeting requirements rather than by maximising or minimising design objectives leads to lack of innovation and increases in cost and time that might be avoided with an informed modification of requirements as part of the systems design process, rather than a forced adjustment (e.g., Collopy and Holllingsworth 2011).

Looking at systems as consumer products makes such concerns more prominent. Specifications as system constraints are there to make sure the product works, but objectives to optimise are what drive the design and its success in the market. The complexity of artefacts like automobiles and smart phones makes the use of systems engineering methodologies increasingly important but with an adaptation to serve a capricious market. The proliferation of smart devices and their bundling with services, in what we now call product-service systems (Sakao and Lindahl 2009), requires a true melding of the two early skills of systems designers – operations-based and physics-based – with the human presence firmly established both in the design organisation itself and in the drivers of the design process.

Systems Design Thinking

Practitioners of systems engineering employ *systems thinking*. Such thinking implies a cognitive ability to perceive the whole more than the sum of the parts, to identify and manage interactions among physical parts as well as among individuals, disciplinary groups, and supplier organisations. Systems designers share the characterization of other engineers as methodical, data driven, and analytical, but they are also characterised as interdisciplinary, creative, flexible, effective communicators, and emotionally intelligent.

Looking at other design practitioners, an obvious comparison emerges to product designers who employ *design thinking*. This term implies a human-centred attitude to design decision-making in product development that "integrates the needs of the people, the possibilities of technology, and the requirements for business success" (Brown 2008). Key ingredients of design thinking are (i) challenging the problem as given by the customer to uncover the true nature of the problem; (ii) understanding the user deeply, e.g., through observation, data, ethnography, and empathy; (iii) generating many conceptual solutions before judging whether they will work; and (iv) using quick, early prototyping to gain insights on functionality and user appeal, and to enable iteration.

The evolution in the nature of systems engineering design discussed above compels an argument that the role of the modern engineering systems designer is one that combines the roles of traditional systems engineers and product designers. The modern engineering systems designer employs *systems design thinking*, a cognitive ability that integrates systems engineering, systems thinking, and design thinking (Greene 2019). The value of such thinking has been recognised by both the product design and the systems design communities, driven by the increased complexity in product design and the increased importance of the human element in systems design.

The Evolving Education Landscape

The concepts of design thinking, systems engineering, and systems thinking originated in the disciplines of industrial design, engineering design (particularly aerospace, electrical, and mechanical engineering), business, psychology, and operations research. The mindset, methods, and approaches core to each discipline were originally developed and taught in the corresponding schools with their own disciplinary objectives. Educational programs of study reflected these disciplinary learning objectives.

Today the mindsets, methods, and approaches from each discipline are challenged by the larger question of designing products and systems for diverse users and stakeholders, and increasingly so by our apparent impotence to address directly through design such wicked problems as climate change and sustainable development. The United Nations pledge toward the 17 Sustainable Development Goals (SDGs) is a potent global message emphasising the multidisciplinary nature of these goals, illuminating the fusion of thinking styles and actions needed to achieve them, and the difficulties in making progress (UN 2019). Such realisations pertaining to designing at large are not new, going back to Papanek (1971) and Schumacher (1973) and more recently to Tromp and Hekkert (2018) and Meyer and Norman (2020).

The education system has responded through modifying curricula to address new topics and new accreditation requirements. A good example is the general criterion for student learning outcomes defined by the US Accreditation Board for Engineering and Technology for all students in accredited programs (ABET 2018):

> "Student outcomes are outcomes (a) through (k) plus any additional outcomes that may be articulated by the program:
> (a) An ability to apply knowledge of mathematics, science, and engineering
> (b) An ability to design and conduct experiments, as well as to analyze and interpret data
> (c) An ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
> (d) An ability to function on multidisciplinary teams
> (e) An ability to identify, formulate, and solve engineering problems
> (f) An understanding of professional and ethical responsibility
> (g) An ability to communicate effectively
> (h) The broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
> (i) A recognition of the need for and an ability to engage in lifelong learning
> (j) A knowledge of contemporary issues
> (k) An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice"

Criteria (c), (d), (e), (f), (h), and (j) are particularly noteworthy and create institutional challenges for educational programs on how to document honestly that they have achieved these learning outcomes. Design experiences are often the most viable way to attempt to do that in curricular and cocurricular activities such as international experiences and field project work in developing countries or in economically depressed regions, and team projects such as designing space experiments or CubeSats for NASA (2017). While some relatively recently founded institutions have embraced this broad concept of design as the organising principle of their curricula, for example, Olin College in the USA and the Singapore University of Technology and Design, established institutions of higher learning have yet limited curriculum-wide adoption.

The professional engineering organisations also offer substantial support for systems engineers. The International Council on Systems Engineering (INCOSE) publishes and updates the *INCOSE Handbook* (Walden et al. 2015). Three steward organisations for systems engineering – INCOSE, the Institute of Electrical and Electronics Engineers Computer Society (IEEE-CS), and the Systems Engineering Research Center (SERC) – maintain the Systems Engineering Body of Knowledge Wiki (SERC 2019, SEBoK 2019a), an open resource compendium of key knowledge sources and references for systems engineering. The website of the abovementioned SERC, a university-affiliated research centre of the US Department of Defense, has a wealth of information including a worldwide directory of systems engineering academic programs. The US National Aeronautics and Space Administration (NASA) has been a pioneer in systems engineering, and its handbook (NASA 2016) is a widely-used reference. The NASA Systems Engineering Research Consortium recently published some general systems engineering principles and hypotheses (Watson et al. 2018, 2019), and a US Air Force Academy book focused on space systems (Larson et al. 2009). Introductory textbooks include Buede and Miller (2016) and Kossiakoff et al. (2011) for general systems engineering; Papalambros and Wilde (2017) for design optimisation and MDO, and Parnell (2017) for more practical trade-off analysis; Oppenheim (2011) for links with six sigma and lean processes; and Maier and Rechtin (2010) and Sillitto (2014) for system architecting. These resources acknowledge the evolving nature of systems engineering education and training.

Context for holistic design thinking can also be gained from Petroski's books on failure (e.g., Petroski (1982, 2006)), while Taleb's *Black Swan* (Taleb 2007), Rich's *Memoirs at Lockheed* (Rich and Janos 1996), Brooks' software systems experiences at IBM (Brooks 1995), and Johnson's exposition on the history and politics in aerospace engineering (Johnson 2006) offer retrospective insights from systems engineering practice.

Roles of Systems Designers

Role is defined generically as "a function or part performed especially in a particular operation or process" (Merriam-Webster 2013) or "the purpose or influence of someone or something in a particular situation" (MacMillan 2019). In a business setting, role is defined as "a prescribed or expected behavior associated with a particular position or status in a group or organisation" (Business Dictionary 2019).

In the present context, we adopt these definitions and discuss the roles of engineering systems designers realised in actual practice, typically in the relevant positions within a large organization. We will discuss the skills associated with these roles in the next section.

The different functions we described earlier make the term "systems engineer" to be a job description with somewhat different meaning in different organisations or industries. Here is a general description from INCOSE (2021):

> Systems engineers are at the heart of creating successful new systems. They are responsible for the system concept, architecture, and design. They analyze and manage complexity and risk. They decide how to measure whether the deployed system actually works as intended. They are responsible for a myriad of other facets of system creation. Systems engineering is the discipline that makes their success possible – their tools, techniques, methods, knowledge, standards, principles, and concepts. The launch of successful systems can invariably be traced to innovative and effective systems engineering.

In earlier iterations, INCOSE described the systems engineer as the primary interface between management, customers, suppliers, and specialty engineers in the systems development process, and stated that, while most have a background in engineering disciplines, the career descriptor also had a lot to do with the ability and interest to think with a systems perspective, which may come from specific engineering fields but also from a science/math, human systems, business, or any field that develops critical and logical thinking. Under "Grow in Systems Engineering," INCOSE further states (INCOSE 2021):

> Unlike other engineering disciplines, which concentrate on specialized technology types or phenomena, systems engineering focuses on the integration of everything that makes a system (or system of systems) coherent and effective, integrating work across those other disciplines. Systems engineers bring a particular perspective to the engineering process, which means they have professional and educational interests that are unique from other kinds of engineers.

Is a systems engineer different from a systems designer? Arguably, the terms imply the same role provided they both adopt the concept of systems design thinking discussed above. Therefore, here we make no distinction between the two.

We can understand the engineering systems designer roles better if we consider that engineering systems design has two distinct phases, conceptual (preliminary) design and embodiment (detailed) design. During conceptual design, the overall systems design must be partitioned into physical subsystems as well as into the disciplines that must contribute design knowledge. During embodiment design, the individual subsystems must be designed in detail and coordinated to meet consistency and mission goals of the overall system. Thus, we can identify two types of engineering systems designer jobs:

Type 1 is an engineer technically responsible for the overall design, performs conceptual design, partitions (architects) the design, and supervises the work of the organisation during detailed design, integration, and testing.

Type 2 is an engineer responsible for embodiment design, integration, and testing. The Type 2 job is to coordinate and facilitate the work of design teams that develop separate components of the overall system.

In traditional systems engineering parlance, a Type 1 designer would be called a system architect, and conceptual design would be called system architecting; a Type 2 designer would be a "standard" systems engineer.

Arguably, the two types overlap and can even coalesce. For example, for simpler projects and smaller design organisations, one individual may embody both types. As project complexity and size of organisation increase, the two types become increasingly distinct (Grogan and de Weck 2016). Following de Weck (2020), a boundary between simpler and more complex systems can be delineated by the cognitive bandwidth of the human mind; using Miller's rule of the "magical number 7 plus or minus 2" for cognitive capacity (Miller 1956), a system with three or fewer levels of decomposition, namely, with $(7+/-2)^3$ or 125–900 individual parts, can be managed by a single human designer. In de Weck's example, a "complex" mechanical watch has 100–150 parts and a single watchmaker can handle every detail of this system.

Multidisciplinary design optimisation (MDO) is a well-recognised function and job specialty in systems design, but its role is often confusing, even within the design organisations. The term originated in the early 1980s in the aerospace industry motivated by the recognition that vehicle design must account for both structural and aeroelastic performance, and that the analyses from each *discipline* (structural mechanics and aeroelasticity) are coupled. Therefore, design optimisation should coordinate results from both analyses. Such discipline-based partition (called aspect partitioning) is different from a physical parts partitioning (called object decomposition). Most design organisations employ a matrix structure to support both. The confusion comes in the use of the term MDO for addressing the coordination of solutions coming from both aspect and object partitioning. In this broader but strictly incorrect use of the term, MDO is practiced by both designer types.

We can now summarise the roles of an engineering systems designer based on the author's experience and advice from the field experts noted in the Conclusion section:

- Formally represent the preferences of all stakeholders (requirements elicitation).
- Identify the proper way of partitioning the system into subsystems (object partitioning or system architecting) and disciplines required for analyses (aspect partitioning).
- Integrate concisely information from the engineering (physics-based) and project (operations-based) disciplines into the systems design to properly represent the system functions and interactions in system use.
- Understand, plan the development, and manage the implicit and explicit prioritised goals and requirements of subsystems for consistency with each other and for the overall system.

- Manage the interactions between different engineering teams, external events (e.g., change in stakeholder preferences), and internal events (discovery that certain technologies are infeasible).
- Make joint decisions involving trade-offs and uncertainty with other engineering teams on behalf of system stakeholders (systems embodiment).
- Forecast how the system evolves over its lifecycle as well as the consequences (including potentially unintended consequences) of different decisions (system dynamics).
- Ensure verification and validation are complete for all implicit and explicit goals and requirements.
- Release the preferred authorised design solution to the entire enterprise (organisation).

In a somewhat informal sense, the role of the engineering systems designer is to:

- Oversee the design and development of a system that
  – Works, i.e., actually performs the functions its designers intended
  – Is efficient relative to competing designs which were not selected
  – Is robust in its output in response to small changes in its input or the environment in which it must perform
  – Accounts for and reduces the unintended consequences of the design
- Ensure the whole is greater than the sum of the parts.

Finally, an often overlooked role for a Type 1 designer is to design the organisation that will perform the Type 2 designer functions. This includes imbuing that organisation with a vision of where they are going and providing compelling and effective technical direction to kick off the design (Triantis and Collopy 2014).

The role of systems engineers has been the subject of several studies, including Sheard and her colleagues (Sheard 1996a, b; McKinney et al. 2015) with some alternative view from Graessler et al. (2018). NASA studied highly effective systems engineers from interviews with a peer group of NASA systems engineers focusing on behaviours rather than skills (Williams and Derro 2008). This and other studies on roles and competencies are included in the SEBoK (2019b). Griffin (2010) articulated the need to rethink the evolving practice of systems engineering and the roles and competencies of systems designers; following this lead, a number of studies have examined these roles, including Frank (2012), Triantis and Collopy (2014), the Helix Project at SERC (Hutchison et al. 2016), Arnold and Wade (2017), Pyster et al. (2018), McDermott and Salado (2019), Collopy (2019), and Greene (2019). There is increased recognition that the roles of systems engineers are and must evolve along with society's expectations for how systems are deployed and operated.

The key takeaway from the discussion here is that the persona of an engineering systems designer within a design organisation has human behaviour aspects such as connector, translator, and facilitator and technical capability aspects such as analyser, organiser, and integrator. Human behaviour is about leadership and facilitation of the work of others in formal or informal management positions. Technical capabilities come from executing the actual systems engineering process steps. This view is consistent with the evolving perception of engineering systems design as a socio-technical enterprise.

Skills of Systems Designers

Skill is defined as “a particular ability that you develop through training and experience and that is useful in a job” (Cambridge Dictionary 2011) and “the ability to use one’s knowledge effectively and readily in execution or performance” (Merriam-Webster 2019). We discuss the skills needed to execute the roles of systems designers. Following the same classification as for roles, these skills can be human and technical. Note that we avoid using the term “soft” for human skills because arguably they can be just as hard as technical ones. The skills included here come from the author’s experience and consultation with the field experts noted in the Conclusions section.

Regarding technical skills, practicing engineering systems designers, as opposed to recent graduates or academics, exhibit the following skills:

1. Type 1 designers must have acknowledged expertise in at least one or two relevant areas. A Type 1 designer must realise that while she/he as leader is like an orchestra conductor, he/she cannot earn and retain the respect of the players without them knowing that their leader has deep technical knowledge in at least one area and she/he once did real, hands-on, deliverable work in relevant areas.
2. Engineering systems designers should have the broadest possible technical, business, management, and education experience. Depth in one or two areas is mandatory, but breadth is everything. Engineering systems designers must be able to make tough cross-disciplinary decisions based on merits. The best engineering systems designers seem to know more than a little about everything.
3. Engineering systems designers should have a sound background in first engineering principles and optimisation which form the basis for model-based systems engineering (MBSE). In particular, they must have the ability to construct and correlate models that are abstractions of interactions (internal and external) and to use the proper set of models (rather than a single one) to analyse system interactions, functions, and performance and to evaluate alternative scenarios against the model. The Type 2 designer needs working skills in the actual MBSE practice.
4. A Type 1 designer should be a “big picture” thinker. She/he must understand, at least at the top level, the system functions, interactions, and application (how it will be used).
5. Engineering systems designers must understand data. One who just records data is a bookkeeper, not an engineering systems designer.

Regarding human behaviour skills, engineering systems designers must:

1. Be "good with people", at least to the extent that he or she is willing to listen to, think about, and resolve fairly the arguments and trade-off decisions that will come to them for resolution. They don't get to make the easy decisions, and the tough decisions will always leave (at least) one disgruntled party behind. An engineering systems designer must make clear that decision-making is rational, systematic, and beneficial for the overall goal, rather than arbitrary, capricious, and personality based.
2. Be inquisitive! Delving into all aspects of a problem is essential and interest in the "big picture" is essential. If it is just a matter of taking the inputs and looking at options, then it must be a trivial problem. The biggest contributions are made by those who delve into the full story.
3. Practice empathetic observation; conduct detailed surveillance of user experiences interfacing with a product or service, and analyse the how, when, where, what, and why of the experience from the user's perspective.
4. Be able to recognise their own limitations and get expert advice. In complex projects, it is impossible to know everything. Engineering systems designers must synthesise complex solutions, and this requires a diverse set of knowledge; they must keep learning as technology is never static.
5. Be willing to engage and challenge others in 360°, asking (good) questions from peers but also up and down the organisational hierarchy.
6. Possess excellent communication skills, both receiving (listening, interpreting) and transmitting (speaking, writing, diagramming, modelling). They must be able to act as translators between engineers in different disciplines, business leaders, and customers – not only for jargon but also for the impact of technical alternatives or changes to non-engineers and stakeholders whose concerns are non-technical.
7. Know how to create a positive teamwork environment, and engage everybody to create a robust solution.
8. Create and articulate a vision. Put forth an idea of the future system situated in the world, communicate this idea to the organisation, and motivate the organisation to pursue this vision.

The above lists are daunting, and one must wonder if any mortal is capable of possessing all these skills. In a true sense, these skills are the ideals that an engineering systems designer strives to acquire and practice, perhaps over a working lifetime (Davidz and Nightingale 2008). What, then, is the feasibility of realising these skills in a practicing systems designer? Can we design an experience that will result in these skills?

As with all design problems, awareness of the need for such skills is the first step, in both the educational and the professional communities. We must start with understanding the needs and wants underpinning the problem (skill generation); deeply study the intended user (the future skilled designer) and the attributes that the problem solution (the educational and professional experience) must have to really solve the problem; explore alternative solutions, prototype, and proceed with selection; embody the concept in an actual education or training program and verify its functionality; validate that the solution attributes are satisfied and the resulting designers have the desired skills.

One may argue that following the above design approach requires a transformation of both the educational and professional communities, where they will work together rather than sequentially, with some rapid prototyping done before too many resources are expended and with proper assessment methods that support iterations. Simply put and without being in a circular argument, we must employ systems design thinking.

The Broader Context

The roles and skills of engineering systems designers must be seen in the broader context of the roles and skills of engineers at large, as well as of the anticipated future jobs in general. There has always been extensive discussion on engineering education and practice, such as Florman's witty, delightful, and erudite articulation of the role of engineering in shaping the world (Florman 1976) to the normative descriptions of how engineers should be in Christensen et al. (2015) to Roth's self-actualisation guide to designers with roots in the pre-design-thinking days of the 1960s and 1970s (Roth 2015).

Perhaps a more telling context are views on future jobs and their attributes. The World Economic Forum (WEF) at Davos has focused on this repeatedly. For example, the WEF report on Social and Emotional Learning through Technology (WEF 2016) makes a strong case: "To thrive in the twenty-first century, students need more than traditional academic learning. They must be adept at collaboration, communication and problem-solving, which are some of the skills developed through social and emotional learning (SEL). Coupled with mastery of traditional skills, social and emotional proficiency will equip students to succeed in the swiftly evolving digital economy". The report classifies the twenty-first-century skills as follows:

- *Foundational literacies* for the application of core skills to everyday tasks; these include literacy, numeracy, scientific literacy, information and communication technology literacy, financial literacy, and cultural and civic literacy.
- *Competencies* for approaching complex challenges; these include critical thinking and problem solving, creativity, communication, and collaboration.
- *Character qualities* for approaching the changing environment; these include curiosity, initiative, persistence and grit, adaptability, leadership, and social and cultural awareness.

A subsequent World Economic Forum report on the future of jobs (WEF 2018) states that future jobs will require understanding technology and data, understanding the impact of technology across multiple domains such human-machine interaction and user experience, and "human" skills – such as creativity, originality and initiative, critical thinking, persuasion, and negotiation – to interact with diverse stakeholders. While the report's projections are stated through 2022, the trend toward integration of understanding both technology and humanity is unmistakable.

Conclusion

To calibrate my formulation of the above roles and skills I sought the advice of several field experts: A. H. Bell, R. Bordley, A. Collopy, P. Collopy, O. L. de Weck, A. Hyde, M. Greene, D. Verma, M. Watson, D. Winter, and an anonymous but well-known senior aerospace systems engineer. While the opinions and interpretations of such advice expressed above are solely my own, there was clear consensus that a modern engineering systems designer is expected to have an unusual combination of abilities as a human being and as a technical expert. How such abilities can be acquired is a separate subject in its own right. We briefly discussed the challenge for a transformative approach in the education community and how it might be addressed using a design thinking approach. For now, the conventional wisdom is that experience, practice, drive, and character predisposition are essential. One may argue that this complex skill set is only necessary for what we termed Type 1 designer who works at the front end of the process but also follows through its execution. This argument is true to some extent, but it would be a mistake to assume that Type 2 designers do not need such a skill set. At a minimum, they need to have a strong appreciation of these skills and to practice them in their daily work albeit at a smaller scale. The good news for a design organisation is that there are much fewer Type 1 designers needed than Type 2 ones. A wise organisation would take advantage of this fact and cultivate its many Type 2 designers to hone their skills so they can assume the Type 1 roles when the need will surely arise.

Wicked problems will remain with us in perpetuity. Many of them are of our own doing, and one might argue that we just need to reform our ways to solve them, climate change being a case in point. One might also argue that such problems are intrinsic to our social organisation and therefore some new ones will surely emerge. To the extent that such wicked problems will be tied to technological intervention, engineering systems designers will be critical agents in mitigating the undesirable effects of these interventions. They must be equipped to fulfil this role.

Cross-References

- ▶ Architecting Engineering Systems: Designing Critical Interfaces
- ▶ Asking Effective Questions: Awareness of Bias in Designerly Thinking
- ▶ Designing for Human Behaviour in a Systemic World
- ▶ Educating Engineering Systems Designers: A Systems Design Competences and Skills Matrix
- ▶ Engineering Systems Design Goals and Stakeholder Needs
- ▶ Human Behaviour, Roles, and Processes

► Introducing Engineering Systems Design: A New Engineering Perspective on the Challenges of Our Times
► Research Methods for Supporting Engineering Systems Design
► Sustainable Futures from an Engineering Systems Perspective
► Technical and Social Complexity
► Transitioning to Sustainable Engineering Systems

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Part V

Futures of Engineering Systems Design

Educating Engineering Systems Designers: A Systems Design Competences and Skills Matrix

31

James Moultrie

Contents

Abstract

This chapter provides a summary of key literature to argue that there has been a gradual change in emphasis in design education, from technical projects, to systems engineering and more recently, the need to tackle complex socio-technical engineering systems problems.

J. Moultrie (✉)
Department of Engineering, University of Cambridge, Cambridge, UK
e-mail: jm329@cam.ac.uk

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In the 1970s, attention was focused on technical or engineered systems, recognising that by only focusing on small sub-systems, problems emerge later with systems integration. In the 1980s, soft-systems methodology recognised that engineered systems are used by people and this critical dimension had not been given sufficient attention. More recently, there is a renewed call for designers to pay attention to increasingly complex socio-technical problems. These problems are characterised by being dynamic (different parts change at different rates), non-linear (do not follow cause and effect relationships), emergent, often of a large scale (e.g. societal transformation), containing significant social and technical complexity and having high levels of unpredictability.

There is growing awareness of the need to equip engineering design students with the skills and competences that are necessary to tackle these complex socio-technical challenges. To help address this need, an original 'systems design competences and skills' matrix for engineering systems design is proposed. This matrix seeks to help design students and educators consider the boundaries around an individual design brief and to consider how a series of design briefs combine to deliver a balanced programme of design education. The matrix is illustrated through six case examples from university engineering programmes, each of varying levels of complexity.

Keywords

Design education · Design brief · Education · Engineering competences · Engineering skills · Engineering systems · Engineering systems design

Introduction

Educating the next generation of engineering designers demands that they are not only able to address complex technical systems, but that they do this with an understanding of the wider socio-technical engineering systems in which these technical systems sit.

Global challenges such as energy supply, sustainability, resource utilisation (and many more), require a new generation of designers who are not only able to conceive of and implement technical solutions, but who have the competences to take a whole systems perspective, to explore complex interactions between sub-systems, the social and technical aspects of a system, and understand that even the smallest of technical projects may have much broader implications.

This chapter provides an overview of relevant literature in design education and discusses how views on systems have evolved from a narrow technical systems engineering perspective to encompass complex socio-technical engineering systems. Recently, there has been a rallying call for much greater emphasis on these broader systems in engineering design education (e.g. de Weck et al. 2011; Costa Junior et al. 2018; Norman and Meyer 2020; Dorst 2018).

Finally, the chapter will look at design education through the lens of design projects, and specifically how design briefs might shape and reflect the scope of the system being addressed. In so doing, a new engineering systems competences and skills matrix is proposed that is intended to be of use by design educators to help increase awareness of the scope of the system being addressed.

Engineering Design and Systems Perspectives

All educational engineering design projects must have a boundary set to establish their scope. A critical component of this boundary is the extent and scope of the system which is being addressed. One way to view this boundary is to consider any engineering design activity as a project that tackles an engineering or a societal ‘system.’

Focusing on System Scope

An early discussion regarding the nature and complexity of engineering design projects was produced in 1974 in the Hansen’s book “Konstruktionswissenschaft” (“Design Science”) (Hansen 1974) which describes an [engineered] system as *“a clearly delimited part of reality which has relations to its environment, a structure and a function”*; where the properties of the system are a function of these three interrelated systems (p. 21). Here, the system is a technical system (e.g. a motor) which may be placed in its context (e.g. in a car) and has a series of functions and a structure which delivers those functions. This perspective is common with many texts on engineering design whose focus is primarily on the engineered or technical system.

For example, in 1978, Pugh discusses how real-life problems can be used in engineering education and describes an example project to improve a company’s materials handling system. Students initially focused on improving a specific part of the machine, before being encouraged to look at the whole system and realising that a more optimal solution is possible by addressing both the materials being handled as well as the machine which does the handling. But, the scope remains a technical one and does not seek to explore the human and behavioural aspects of underlying the system.

This example establishes an important principle in the design of complex systems, which is the extent to which the assumed problem boundary is fixed and whether or not students are encouraged to think beyond the immediate system constraints to consider a larger problem space.

For many design educators, the primary element of concern remains the technical system. Hubka and Eder (1987) suggests that different types of design have a specific ‘object’ of the design activity and that in ‘engineering design’, the object is the ‘technical system’, including machines, machine elements, and components. Eder (1988) synthesises multiple definitions of engineering design and comments that “engineering design is a process [. . .] through which information in the form of requirements is converted into information in the form of descriptions of technical systems, such that this technical system meets the needs of mankind” (p. 169). Again, the emphasis is on the technical system.

Simon (1981, pp. 26–28) describes a complex system as having “many components having many relations among them, so that the behaviour of each component depends on the behaviour of the others.” He goes on to note that systems are constructed in ‘Levels.’ Complex systems have a hierarchical structure that are [nearly] decomposable into smaller systems. Thus, systems are inherently ‘fractal’ in nature in that it is usually possible to sub-divide any system into smaller sub-systems, or indeed that a system might also be viewed as part of a larger super-system (Hubka and Eder 1987, p. 128). In this hierarchical view, any individual element in the system can be modelled in the same way, with both sub- and super-systems. The notion of nested sub-systems is picked up by many works and relates directly to the concept of system integration. For example, Padgett (1999) describes the use of a complex technical system as a basis for teaching engineering design, where sub-teams of students develop individual sub-systems which require subsequent integration at a full system level.

Reich et al. (2006) in describing the development of a mechatronics course, views ‘systems thinking’ as one of the key learning outcomes. Here, the system is the electro-mechanical system. This resonates with Sobek’s (2006) perspective, where system-level design is characterised by the arrangement of *‘components and sub-systems and design of interfaces.’* Sobek views this as a specific part of the design process *‘systems-level design’* and defines this as the *‘exploration of and decisions about what the components and subsystems are and what their function will be; the basic geometry of the different pieces and how they will be arranged, including location, orientation, and grouping; and how the pieces will connect or interface together and with the environment’* (p. 533).

Sobek and Jain (2007) studied student design practices and concluded that system-level design work is of high importance and results in higher quality designs.

Introducing System Integration Through Systems Engineering

However, systems integration can be more problematic than simply combining the sub-systems with the hope that the system will perform as expected, even if all of the individual sub-systems appear to be working to specification. Discussing engineering ‘Capstone’ courses, Noble (1998) observed that ‘the challenge facing engineering educators is to provide an education that gives students the tools to analyse integrated problems in a systems context that emphasizes optimizing the system rather than the component, with respect to the engineering design knowledge and techniques they have learned’ (p. 198). Noble was specifically referring to systems thinking to encompass the product as well as its full production system.

In discussing systems, several authors consider the design and development of mechatronic systems (e.g. Wang et al. 2013). Wang et al. (2013) adopt a modified Vee-Model of design (Fig. 1), which is commonly used in the context of systems design as a basis for teaching the design of mechatronics systems. The left hand side of the Vee relates to the design sequence and the right hand side to prototyping and implementation. Projects described include: a bottle sorting system; and an inverted pendulum. The Vee model is interesting as there is a direct interplay between component and system level analysis. Indeed, Deininger et al. (2017) notes that *“Working with prototypes at the component level and the ability to switch between*

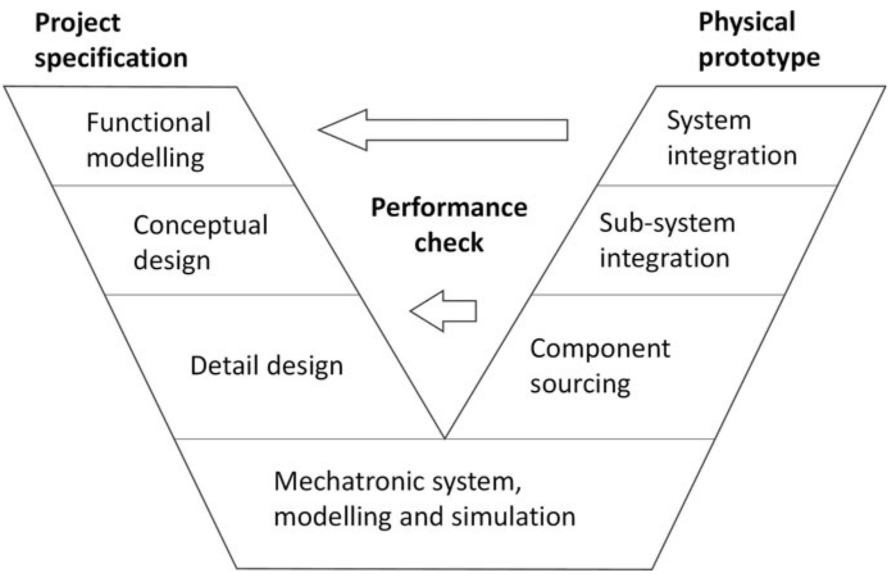

Fig. 1 A typical systems design Vee model. (Illustration by author, based on Wang et al. 2013, p. 943)

component- and system-level thinking are crucial to successful design as practiced by design experts," referencing Hilton (2015), Viswanathan et al. (2014).

Thus, for a long time, the dominant view in engineering design education has been built outwards from the core technology, through products towards larger technical systems. The often cited 'ABET (Accreditation Board for Engineering and Technology) criteria' are frequently used to underpin many design courses describe engineering design as being "the process of devising a system, component, or process to meet desired needs within realistic constraints" (ABET 2011). Goncher and Johri (2015) noted that "design, in its multifarious forms, is an integral component of engineering practices; consequently, engineering education strongly emphasises the design of systems, components, or processes (ABET 2011)."

Introducing System Views Through Soft Systems Approaches

In two seminal articles in 1981 and 1985, Checkland (1981a, 1985) introduces the notion of 'soft systems', especially as applied to Operations Research, recognising that technical (or hard systems) sit within the context of human use and behaviour and that traditional systems engineering does not work "when applied to messy, ill-structured, real world problems" (p. 763). These problems may be difficult to define, have multiple elements with competing priorities and multiple stakeholders each with different needs.

These ‘soft systems’ relate to human activity, where there is an *“ill-defined awareness that a change is needed, no clear criteria for evaluating directions of change and a few mathematical relationships between the various elements of the system.”* Checkland (1981b) claims that ‘hard systems’ are a special case of the more general ‘soft systems.’

Checkland represented his Soft Systems Methodology with the graphic shown in Fig. 2. This representation seeks to show the non-linear nature of these problems and that significant effort may be taken in understanding the fundamental nature of the problem situation itself. With no clear starting point, Checkland describes the interplay between the development of models and perceptions of the real world and their comparison in order to identify changes that are systematically desirable and culturally feasible. To do this, requires reflection on the problem situation and understanding of the *Weltanschauung* or point of view from which the system is being described (with the example that one man’s ‘terrorism’ is another man’s ‘freedom fighting’). In this model, CATWOE is an acronym to describe:

- **Customers**: victims or beneficiaries of the system
- **Actors**: who carries out the activities in/of the system
- **Transformation Process**: what inputs are transformed into what outputs by/in the system
- **Weltanschauung**: what image of the world makes this system meaningful

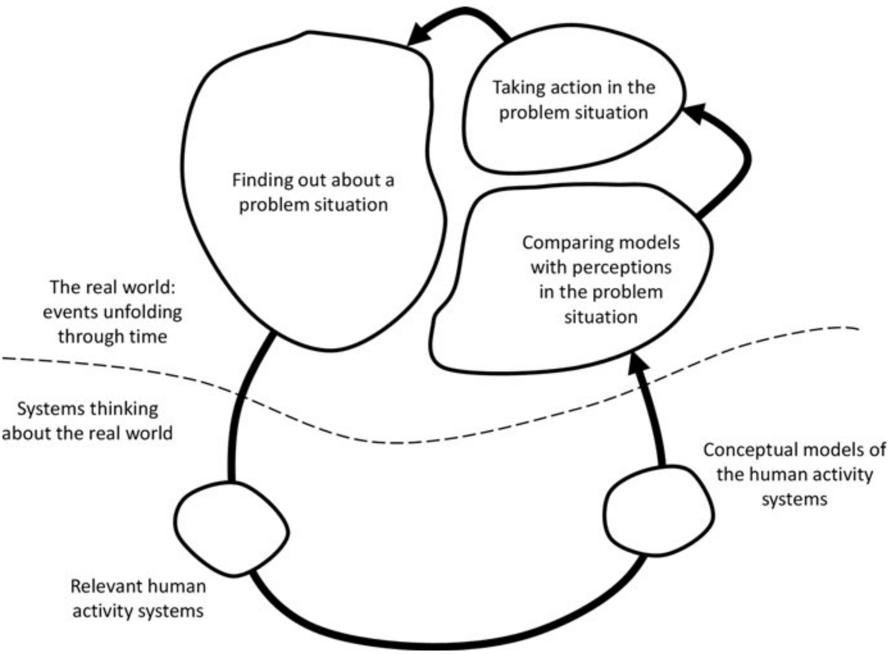

Fig. 2 Soft Systems Methodology. (Illustration by author, based on Checkland 1985, p. 763)

- **Owner**: who could abolish this system
- **Environmental constraints**: what external constraints does the system take as given

The root definitions are the different features of the system, with reference to these CATWOE elements. The emphasis on Customers, Actors and Owners recognises that there are multiple complex stakeholders influenced by the system and each of these may have different perceptions of the problem system. For example, a company discussing their product range *"will quickly reveal different perceptions of the relevant worlds: what at the operational level may be agreed problems quickly become, at higher levels, issues created by clashing norms, values and Weltanschauungen"* (p. 765). The resulting models that emerge are thus *"relevant to arguing about the world, not models of the world; this leads to 'learning' replacing 'optimizing' or 'satisficing'; this tradition talks the language of 'issues' and 'accommodations' rather than 'solutions'"* (p. 765).

At a similar time, Nadler (1985) was discussing the need for engineering design problems to look more widely than the boundary of the technical system to understand wider economic, social, human and political considerations (Nadler 1985). He called this 'Systems Methodology and Design' (SMD) and noted *that "there is a need to see a design project as part of a larger system that interacts with the outside world, and in particular, with the economy as a whole."* Nadler reacts against the notion (still commonly held) that a design can be decomposed into *"simple indivisible parts,"* each constituting a problem which can be solved in isolation and later aggregated to form a whole design, claiming that this may produce optimal sub-systems, but at the expense of effective performance of the wider system. Instead, he suggests that all systems and sub-systems should be considered as part of larger systems, with emphasis given to the whole, not the individual parts. He makes a rallying call for design educators to provide students with real-world problems, where they may not initially have advance knowledge and which require consideration of the interrelationship between technology and society.

Voute et al. (2019) summarise the key challenges facing design today, including a transition from single mass-produced products to product-service systems and towards systems with many components and actors. They claim that design is now entering the 'systemic level', contributing to systemic and complex problems. As a result, students need specific skills in bringing together teams of designers from multiple disciplines. Oehmen et al. (2015) suggest that in addition to complex problems, it is possible to identify 'chaotic' problems, where the relationships between cause and effect are impossible to determine due to constant turbulence.

Systems Not Stuff: Complex Socio-Technical Engineering Systems and 'Big Problems'

One of the primary challenges in considering a systems-approach is a lack of clarity and consistency in how the terminology is used. As we have seen, some consider the system to be the technological system (e.g. Otto and Wood 1998) and others that the system boundary encompasses the wider socio-technical system (e.g. Checkland 1981a). In some cases, where the technical system is highly complex, the system might incorporate multiple sub-systems, which are complex in their own right (e.g. Padgett 1999). In comparatively few cases (e.g. Nadler 1985), the system is viewed as being broader still, embracing economic, political and social concerns. Others take a less precise view, suggesting that a 'systems orientation' is one in which the designers consider *"the integration and needs of various facets of the problem"* (Sheppard and Jenison 1996).

It is only when we begin to consider the wider implication of the things that we design that the need to consider the system beyond the boundaries of the product become apparent. This is especially the case for critical topics such as sustainability or inclusive design. For example, it is possible to improve a product's sustainability within a product-level system boundary (e.g. to reduce the amount of plastic used). But, to fully address sustainability challenges, designers must fundamentally understand the nature of production and consumption and how their work sits within this broader system.

Pineda and Jørgensen (2018) emphasise the importance of wider systems thinking in teaching the design of sustainable systems. Interestingly, they define 'systems' by firstly articulating what a system is *not*. They note that: "*Projects aimed at creating new technical energy systems, or transport systems (autonomous vehicles is the most recent hype!), or communication systems, might be very interesting, but when they are framed as pure technical projects it is because a political decision of excluding the influence of relevant actors (including citizens and all kinds of institutions) has already been taken*" (p. 2487).

Instead, they view systems projects as one in which the technical component sits within a much wider network of actors and stakeholders often with competing goals. Pineda encourages students to focus on the 'system representation' in which students are asked to map the complete socio-technical system. In that way, traditional 'concept design' is reframed as the development of systemic concepts. The author notes that a challenge for students is to develop concepts which tackle the 'system-level' and not just one sub-system or technical element. This perspective takes the boundary of design projects beyond what might be more usually seen in product design or even product-service design examples, in which the product or technology is the dominant component. Pineda and Jørgensen (2018) note that:

> A system design process is thus a systematic attempt to reduce complexity by producing multiple mappings and descriptions at first. Then is about conceptualizing different solutions that exist at the systemic and inter-systemic level, not at the level of components or subsystems. And when a concept is selected is about describing it, structuring it, prototyping it and most importantly circulating and exposing it to different actors to test it. (p. 2493)

Sustainability is an issue for which a broader systems-wide approach is strongly advocated (e.g. Ameta et al. 2010). Design decisions need to be considered as having an impact long-term and systems-wide and thus students need to understand these broader implications (Cardella et al. 2010). Cardella et al. also note that systems are inherently interconnected and changes in one system can have unforeseen impact on other systems. Devendorf (2011) describes the importance of considering how global, economic, environmental and societal factors can influence the design of engineered products and systems. They note that consideration of these factors highlights that engineering is *"no longer a profession driven entirely by technical issues – engineers must now understand the global implications of their decisions on social communities, corporate economics and the environment"* (p. 9). Telenko et al. (2016) states that *"Creative resource utilization is crucial for sustainable development and requires big picture and system level thinking that is also useful for delegating tasks within the design process and working in teams."*

Such complex socio-technical engineering systems include, inter alia: food provision, health and social care, transportation, infrastructure, energy, sustainability and education. Problems and opportunities in these domains are characterised by multiple actors with different needs, interactions of complex technology and the potential to explore options from multiple different perspectives. Here, the product (or technology) is just a small part of the potential solution space.

In 2001, Buchanan observed that there had been a *"widening of the scope of design away from individual objects to systems of products and to the broader systems within which products must function in natural and cultural environments"* (p. 14). He suggested that the idea of a 'system' has evolved from systems of 'things' to human systems, environmental systems, and cultural systems.

The Challenge for Design Educators

There is thus general consensus that addressing society's bigger challenges is now widely recognised as being a systemic issue. This is tackled head on by Costa Junior et al. (2018), de Weck et al. (2011), and Dorst (2015, 2018), who all claim that new 'systems design approaches' are needed. Costa Junior et al. acknowledge that despite growing awareness, this has received little attention in design education programmes. The claim that a systems design approach is:

> a mental model through which design engineers can frame the world using systems thinking. Systems thinking is a powerful problem-solving approach for the analysis and synthesis of the entities and their relations in complex phenomena ... [that] guides problem solvers in how to interpret and embed the following into design thinking and practice to handle complex problems situations and design better systems: a systems mindset (e.g. radical holism); systems approaches (e.g. Hard Systems, Soft Systems, and Critical systems approaches); systems methodologies (e.g. Soft Systems Methodology, Systems Engineering, and Critical Systems Heuristics); systems skills (e.g. complexity-handling and human centred perspective); and systems tools (e.g. systems maps, rich picture, and causal loop diagrams) (p. 67).

This lack of attention to complex and systemic problems is echoed by Norman and Meyer (2020), who suggests that many centres of design education remain fixated on teaching traditional design skills and that to tackle these larger, more systemic problems, then design education must evolve beyond its primary focus on the deep specialisations that ground them (e.g. as industrial designers) (p. 20).

By widening the scope of the boundaries that we may place around design problems means that designers are tackling an increasingly *"complex, human-built world that includes ambitious large-scale engineering projects … making engineered products and systems increasingly complex [by] … increasing the number of components and their interdependencies"* and as a result, engineering designers require specific skills to help them cope with increasing levels of complexity (Dym et al. 2005). New skills and competences are therefore needed in order to prepare our designers for the challenges of the twenty-first Century (Weil and Mayfield 2020).

Establishing Boundaries for Engineering Systems Design Projects

Design projects are the central component of all design education (Dym et al. 2005). Whilst it is possible to lecture on technological principles, conceptual models, theories or examples, it is widely believed that design is best learnt through practice, feedback and reflection.

We have seen that design projects may be highly constrained and narrow in scope, or may address large and complex socio-technical engineering systems. The broader the scope of the project, the more this has an impact on the skills, knowledge and capabilities needed to tackle the project (Costa Junior et al. 2018).

'Technical' knowledge, including, *inter-alia,* mechanics, electro-mechanical systems, production processes and technologies, and materials provides a foundation upon which much engineering design is built. In addition to this technical knowledge, budding engineering designers must acquire cognitive capabilities (including design methods or a 'designerly' mind-set) and develop a set of 'craft' skills including the use of representational, hand-craft and modelling skills to develop prototypes or the use of complex IT systems to aid in representation and analysis (Conway et al. 2011; Shah 2005; Lewis 2002). Students also need the ability to identify and use appropriate domain knowledge which is relevant to the specific design problem. For highly constrained design problems, the work may be 'solo' but as problems and thus the design brief grows in scope, then projects are likely to be a team based activity, demanding skills in group work and management (Davis et al. 2010). In addition, many of the underpinning technologies are changing; new production technologies and new CAD and prototyping methods are influencing the way we design. Carelton and Leifer (2009) comment on the need to teach budding designers both 'hard and soft' skills.

In determining the scope of an educational design project, choices must be made on the boundary around the problem being set and its alignment with specific learning outcomes (Goncher and Johri 2015). Without boundaries, or constraints to a design project, the scope and therefore range of potential solutions can be overwhelming, especially for more novice designers. The narrower the boundary we place around a system, the narrower the set of skills and knowledge that are needed to address it. This determination of boundaries and constraints in design problems is thus a critical task for the design educator. For inexperienced designers, high levels of constraint enable the budding engineering designer to wield their design tools with little or minimal risk of failure. Goncher and Johri (2015, p. 254) argues that *"when designers are faced with too many choices, their evaluation and selection processes become costly in terms of the resources used; therefore, optimal constraints are critical for a successful design outcome."*

But, few 'genuine' problems have narrow or easily delineated boundaries. The bigger challenges have wider societal and global impact and thus require highly unconstrained design briefs, which by their very nature integrate multiple different areas of specialist knowledge (Norman and Stappers 2015). Furthermore, many problems may at first appear to be technological, but a little probing may stretch the predetermined constraints with solutions that influence a much wider socio-technical system. Indeed, it is often essential for students to challenge the assumed boundaries in order to truly understand the wider impact of potential solutions on society, the environment, and the economy.

Often, in an explicitly narrowly constrained problem (e.g. redesign the form of a mobile phone), there are inherently wider impacts on society, the environment, and other complex socio-technical systems that a student might beneficially consider. All design decisions have broader and sometimes unintended consequences (Walsh et al. 2019), some of which might not be instantly apparent to a student operating within a highly constrained brief.

It is thus evident that we need to equip the next generation of engineering systems designers with the skills, knowledge, cognitive capabilities and tools to address these larger systemic problems. This presents a genuine challenge for design educators in setting design problems which reflect this new reality but which are also educationally robust. Furthermore, the nature of any design project undertaken by students provides a window into the pedagogical assumptions underlying that exercise. These assumptions are typically embodied in the 'design brief' that must, by its very nature, contain constraints (e.g. cost, time, complexity, production technologies, functionality, etc.) to place a boundary around the specific design exercise. This boundary may be highly specific of may be non-prescriptive (Oliveira and Marco 2017).

These constraints place a limit on what the student might be expected to do and make the exercise 'possible.' Constraints might be practical or logistical (e.g. limiting the number of pages in a submission, hand-in deadlines, etc.) but they also reflect the underlying learning objectives and pedagogical expectations of the specific piece of work. In this sense, constraints can be related to either the design process, the expected design outcome or the resources available to complete the task. Tavakoli and Mariappan (2000, p. 330) noted that *"at the heart of effective teaching of engineering design there must be attention to realistic constraints."*

Several studies have explored the impact of constraints on creativity (Noguchi 1999; Childs et al. 2010), with more constrained briefs believed to limit creativity and more open briefs being used to help students learn how to 'frame' a problem through reflection and iteration (Oliveira and Marco 2017). Other work looks at the effect of different types of design constraints (e.g. sketching, CAD, prototyping) on specific cognitive effects of designing such as fixation and creativity (e.g. Lemons et al. 2010; Viswanathan and Linsey 2012; Viswanathan et al. 2014; Youmans 2011; Kiriyama and Yamamoto 1998).

There are differing views on the extent to which problems should be 'open' and thus demand interplay between problem framing and solution finding. Nicolai 1998, p. 10 noted that

> The engineering curriculum must let the student experience being an engineer by introducing problem situations which force the student to link engineering theory to real world problems by doing some original thinking, evaluating alternate solutions, making a decision and defending it. The best way to do this is by giving the student open-ended problems, since these are the only type of problems that occur in industry.

Whilst such 'open' problems might have relevance to real applications and especially those of a wider systemic nature, some design educators believe that there is also value in more 'closed' design briefs that test specific elements of design knowledge. This classification of design briefs as 'open' or 'closed' is common in the literature. However, this classification is limited, as a brief may be 'open' for some dimensions (e.g. possible manufacturing routes or the nature of the submission format) and 'closed' in others (e.g. technical parameters or timescale).

Individual project briefs may be derived from a perceived need, or may be driven by collaborators. Students may also identify potential opportunities, which are essentially boundary free. Whatever the origin of the brief, each individual brief says something specific about the educational assumptions and expectations for that project. It is also interesting to consider how a student's overall education is shaped by a sequence of design briefs, spanning their whole educational programme. The way in which these briefs progress over the duration of a course, and collectively seek to establish design competences also provides a window into the underlying pedagogical rationale of the whole programme.

If we accept that students must be exposed to a much broader range of design problem, with a focus on the wider socio-technical system, then this has implications for the skills, knowledge and competences that designers need to develop.

This is not to say that more traditional skills and knowledge are no longer relevant, but instead that in addition to these, a broader set of abilities might also be needed.

- **Skills**: Designers often have a 'toolbox' of skills that they can apply when tackling a design problem. Core amongst these are the 'craft' based skills of representation and communication, based around sketching, drawing and modelling. These manual skills are often supplemented by very specific computer based skills such as the operation of CAD systems and the use of modern digital design tools. In addition, designers might gain expertise in using a variety of specific design tools and methods which can be brought to bear on a variety of design problems. There is a plethora of such methods available, including Quality Function Deployment, Design for Assembly, Design Structure Matrices, User Observation and many, many more.

- **Knowledge**: We might make a distinction between the accumulation of general technical knowledge and the specific knowledge needed to address a particular design brief. This type of knowledge is often accumulated as a result of actually working on the project. For example, whilst working on a problem to develop shelters for disaster relief, the designer might develop domain specific knowledge about the materials available the local environment. The designer might also apply their technical knowledge relating to engineering structures to conceive of potential solutions using the available materials. In framing design briefs, it may be anticipated that students only apply accumulated technical knowledge and that no domain specific knowledge is required. A design brief might also be targeted at a very specific technical topic (e.g. optical sensors), requiring application of taught content, but no development of new knowledge. These more traditional design briefs reflect much engineering education which has *"traditionally been taught in a deductive mode, from the bottom up, from component to system"* (Palmer and Hall 2011). In contrast, more complex systems problems however will inevitably require the development of new knowledge based on research into the wider system as a whole.
- **Design related competences**: Irrespective of the nature of the design brief, there are broadly accepted generic design competences that students need to develop. These relate to how we might set about tackling any design problem, including being able to: fully explore the potential solution space to conceive of a wide array of alternatives; think iteratively in order to reconsider ideas when more information is available, without being fixated on previous ideas; and coping with inherent problem ambiguity, where all of the parameters are not clearly known at the outset. It is also widely accepted that underlying competences in teamwork, communication and leadership are also important.
- **System design competences**: As we progress to system level problems (either technical systems or societal systems), a further set of competences are required. Firstly, and somewhat tautologically, is the ability to take a systems perspective, or adopt what many label 'systems level thinking' (e.g. Telenko et al. 2016). This systems level thinking includes the ability to switch between component and system-level thinking (Deininger et al. 2017). More tangibly, Maya and Gómez (2015) describe 'Systems thinking' as relating to *"complex problems and relations between elements; non-linear thinking; team working; decision making processes."*

It is apparent that there is a wide array of design problems that can be tackled during a typical engineering course. These vary in scope from those which seek to test the application of a particular engineering theory all the way to briefs which seek to tackle major global crises. A report from a 'visiting professors' scheme in the UK focusing on educating engineers in design (RAE 2005) noted that the outcomes of design projects may be one of four things: major one-off project (e.g. large bridge);

consumer product (e.g. kettle), process (e.g. traffic management), or a system (e.g. mail delivery). This particular perspective sees a system as an alternative entity, rather than considering the kettle, bridge or traffic management outcomes to be either specific systems or to operate as part of a broader system in their own right. This categorisation also misses the potential for other types of project, such as a project which seeks to develop a particular design skill (e.g. CAD skills) or a project which aims to apply specific engineering theories (e.g. bending moments).

In addition to variations in the nature of the problem being tackled, there are also a wide array of skills, knowledge and competences that also need to be acquired. The breadth of potential projects is fantastic, but it presents design educators with a genuine dilemma. How should this complexity be navigated? In framing a design brief, is it always clear to educators what the assumptions are in terms of the underlying learning objectives?

The design brief embodies assumptions around the nature of the problem, the skills and knowledge being developed and evaluated and the inherent complexity and probably boundary of the system being tackled (Fig. 3).

System Scope

We have seen so far that the notion of a 'system' can include both the technical system and also the wider social-system in which the technology might sit. We have

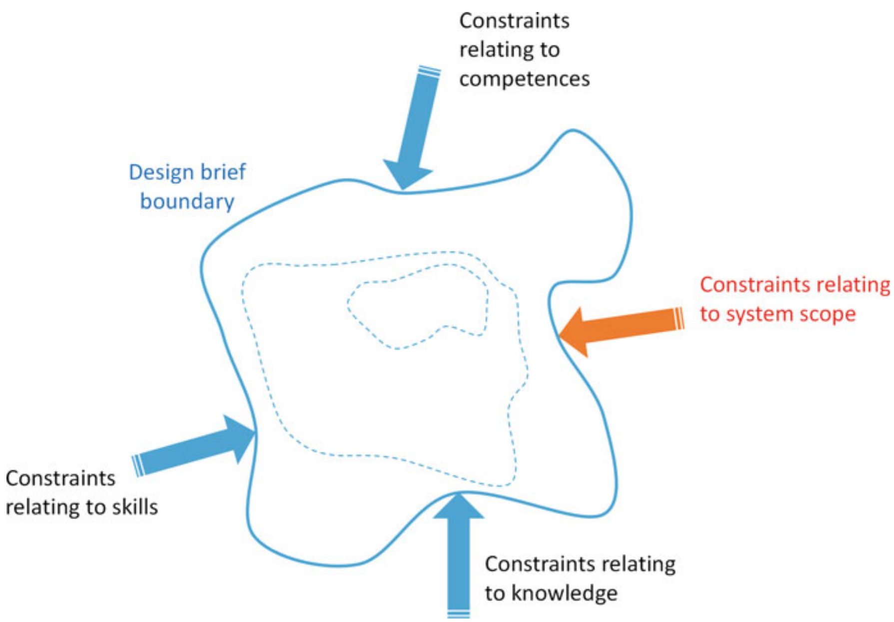

Fig. 3 Establishing the boundary in a design brief. (Illustration by the author)

Fig. 4 Social and technical system complexity. (Illustration by the author)

also seen that the scale, complexity and interrelation between these systems might vary greatly in scope. Figure 4 aims to illustrate this spectrum of potential projects.

Students might be given a set of problems which tackle a discrete technical system, in which there are few social implications. Norman and Meyer (2020) describes these as ‘performance’ problems, and provides the example of a lighting system in which students might need knowledge of materials and manufacturing processes. These engineering problems might also focus on more complex technical systems that require collaboration between different team members. Where the project boundary is largely describing a complex technical system, then systems integration is commonly viewed as being a critical element. It is not uncommon for technical sub-systems to be developed by discrete sub-teams, meaning that integration is often where problems become apparent.

In contrast, a social system problem addressing the needs of multiple stakeholders might have a range of technical but also not technical solutions. Again, these problems might exist at different scales, from a local solution for the provision of healthcare in rural Namibia (problems Norman describes as contextual) to the solution of global poverty or hunger.

In addition to considering the scope of a system in terms of its ‘components’, it is also helpful to acknowledge that systems also have different innate properties. For example, Lammi and Becker (2013) describe complex systems as being:

1. **Dynamic with respect to time**: with different elements evolving and changing at different rates
2. **Non-linear and unbounded**: and therefore do not follow simple cause and effect relationships
3. **Emergent**: having multiple interconnected variables with emerging and changing interactions that cannot be viewed in isolation to understand the aggregate system

They quote Dym et al. (2005) who noted that *“the hallmark of good systems-designers is that they can anticipate the unintended consequences emerging from interactions among multiple parts of a system.”* They also reference Katehi et al. (2009) who describe a system as an “organised collection of discrete elements designed to work together in interdependent ways to fulfil one or more functions ... systems thinking equips students to recognise essential interconnections in the

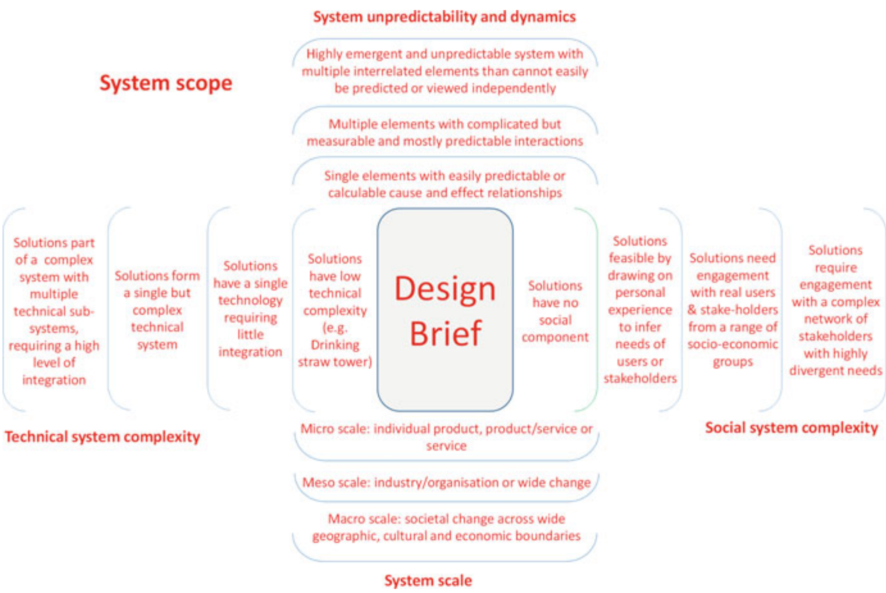

Fig. 5 Full system on the design brief, including social and technical system scope, system scale and system unpredictability and dynamics. (Illustration by the author)

technological world and appreciate that systems may have unexpected effects that cannot be predicted from the behaviour of individual systems." (p. 91).

Figure 5 expands on Fig. 4 to illustrate the potential characteristics of socio-technical problems across four dimensions:

1. **System scale**: Macro (e.g. societal transformation), Meso (e.g. industry and organisational transformation) and Micro (e.g. product-service and individual transformations)
2. **Technical complexity**: Exists on a scale from simple (i.e. few parts/subsystems with performance predictable), complicated (multiple sub-systems) and complex (multiple sub-systems with many relationships and interconnections between them). For complex technical systems, performance is not easily predictable based on evaluating performance of the sub-systems and there are innumerable potential solutions.
3. **Social complexity**: Exists on a scale from simple (few stakeholders, needs easily determined), complicated (multiple stakeholders) and complex (multiple complex and competing relationships with different goals, behaviours and motivations). For complex social systems, the behaviour of the system in response to specific interventions is not easily predictable and there are innumerable potential solutions.
4. **System unpredictability and dynamics**: As the impact of interventions on complex (technical and societal) systems is not easily predictable, then designers may seek solutions that are easily reconfigured or adapted, in response to events

rather than seek to predict and control the behaviour of the system. Causal relationships are not easy to observe and may change dynamically over time and may not be observable in the short term.

With these dimensions in mind, the framing of both problems and solutions becomes much more abductive in style, with designers needing to embrace high levels of uncertainty and constraints placed on the design brief which may be inherently mutually incompatible. In contrast to deductive or inductive reasoning, abductive reasoning is characterised by having multiple simultaneous 'unknowns' (e.g. who, what, how and outcomes). Deductive reasoning is characterised as following a series of logical steps to derive a conclusion which is logically true. Inductive reasoning uses evidence of past occurrences to derive a likely truth (Kolko 2010). Abductive reasoning seeks to develop a 'best explanation' based on insights from observations and experiences. A key characteristic of design is the development of solutions in a context of multiple unknowns and many view design to be a form of abductive reasoning, where experience, evidence and intuition result in new insights and proposals. A detailed description of abduction in design is provided by Kolko (2010).

This abductive approach is somewhat contradictory to traditional models of the engineering design process in which problem definition and specification precedes conceptualisation which in turn precedes detailed design, often following a classically 'prescriptive' design process. For highly complex problems, the generation of potential solutions may progress hand in hand with an emerging understanding of the underlying problem. It is therefore not possible to follow a rigid design process in which one step leads inexorably to the next.

Commenting on the work of students addressing a renewable energy challenge in Uganda, Costa Junior et al. (2018) noted that:

> As a result of their strong technical orientation, students tended to approach the design problem by working directly on detailed (sub) solutions. Such a premature approach resulted in faulty conceptual development and limited the opportunity to form open-ended solutions from which new analyses and reflections could be drawn to formulate a better solution. (p. 75).

The nature of the design problem that is provided to students can be seen as representing the embodiment of assumptions around the scale or scope of the system which is under consideration. Clearly constrained and well-defined problems tend to favour students seeking the single 'correct solution', whereas more open design briefs enable a much broader response, but correspondingly can be problematic for students seeking a clear path to an 'answer.'

For these larger problems, insights cannot easily be developed by listening to lectures or by running experiments in the laboratory. Instead, design projects provide a vehicle by which the skills, knowledge and expertise might be best developed. However, by their very nature, problems of this type are not easy to define or articulate. Previous research has demonstrated that when problems are well-structured (i.e. clearly bounded systems), students are more easily able to produce solutions than for problems which are less well-structured and *"articulating the right problem . . . is more important than being able to solve perfectly the wrong problem"* (Subrahmanian et al. 2003, p. 76). As a result, problem formulation and boundary setting become critical design tasks. Recognising that these present a large diversity of design problem, Norman notes that *"we need a design curriculum that provides options, allowing different individuals to select which level of problem they wish to address"* (p. 16).

A Systems Design Competences and Skills Matrix

Drawing together these multiple dimensions, Fig. 6 presents a 'Systems Design Competences and Skills Matrix.'

This matrix seeks to enable the design educator to establish the characteristics of a design brief along the four dimensions described above (skills, knowledge, competences and system scope). It recognises that students tackling design problems may do so with varying levels of ability, from *Novice* through to *Professional*, where a *Novice* is a first year Undergraduate, *Advanced* is a student in their final year and *Professional* relates to the abilities you might expect in a designer a few years' post-graduation.

The use of this matrix will be described through application to a range of different design projects, with examples taken from the public domain as well as some specific examples from student design projects on engineering programmes.

Using the Systems Design Competences and Skills Matrix to Support Design Education

By considering any design project as being bounded by a series of constraints, it is possible to ask further questions about how design knowledge, skills, and competences are developed. In this section, we provide some examples of real design projects, mapped against the matrix.

Example 1: Simple Straw Tower

A common introductory design project might see novice students set with a brief to design a simple structure out of straws. This could be a tower or a bridge. More advanced students may make specific connection to theory on buckling, tension and compression in structures. Here, there is very minimal systems complexity, a very low level of design skill (i.e. no Computer-Aided Design (CAD) platform, no specific craft-skills required) and a relatively low level of either domain specific or technical knowledge needed. Instead, what is being developed is basic skill in

	Design skills needed			General design competences needed				Knowledge needed		System design competences needed				
	"Craft" skills	IT or Software skills	Design methods or tools	Dealing with problem ambiguity	Ability to think iteratively	Ability to explore the solution space	Professionalism	Technical knowledge	Domain Specific knowledge	Ability to take a system perspective	Technical system complexity	Social system complexity	System dynamics and unpredictability	System scale
Professional / expert	A high level of expertise in sketching, drawing or production of prototypes essential	Specialist SW and/or advanced SW skills are essential	Highly advanced application of multiple design methods	Ability to deal with high levels of ambiguity where both the problem and the solution will evolve iteratively	Can progress through multiple idea, test and evaluation cycles at different system levels	Can intuitively explore the whole solution space with feasible alternatives, avoiding design fixation	Integration of activity from multiple groups, complex system interfaces and deliverables	High levels of technical specialism needed	Domain specific knowledge or expertise is essential	Can rapidly zoom in to details and out to system to see impact of all design decisions	Can develop a system with multiple technical sub-systems, requiring a high level of integration	Can engage with a complex network of stakeholders with highly divergent needs	Can embrace highly levels of emergent behaviour with interrelated elements than cannot easily be predicted	Able to work at a macro scale: societal change across wide geographic, cultural and economic boundaries
Advanced	Advanced drawing and making skills needed	Advanced SW skills (e.g CAD, CAM) required	Application of advanced or topic specific design methods	Ability to deal with an open and ambiguous brief, requiring work to scope and specify constraints	Can conceive solutions at system and sub-system level, with some iteration as the design progresses	Can conceive of a diverse set of feasible ideas at system and elemental levels	Large group activity, multiple deadlines and tasks requiring significant teamwork	Advanced technical or engineering knowledge needed	Some domain specific knowledge is beneficial	Understands relationship between distinct elements of the system	Can develop a single but complex technical system	Can engage with real users & stake-holders from a range of socio-economic groups	Can embrace multiple elements with complicated but measurable and mostly predictable interactions	Able to work at a meso scale: industry/ organisation or wide change
Basic	Basic drawing and making skills needed	Need to operate basic design related SW packages (e.g. CAD)	Formal application of generic design methods (e.g. QFD, etc.)	Ability to deal with clearly specified constraints for critical elements with a small amount of ambiguity	Ability to conceive an initial solution and to progress with minimal iteration	Able to use structured approaches to propose several alternative solutions	Individual activity, self managed	Knowledge of basic technology and engineering required	Can rely on general knowledge	Can consider different parts of the system independently	Can develop solutions with a single technology requiring little integration	Can draw on personal experience to infer needs of users or stakeholders		
Novice	A low level of craft skills required (e.g. basic drawing, making etc)	No specific IT or software skills needed	No specific design methods applied	Ability to deal with minimal ambiguity in the brief, all constraints specific and clear	Ability to develop a single solution to a simple system through trial and error		Ability to develop a single solution to a simple system through trial and error	No specific technical knowledge needed	No specific domain knowledge needed	Ability to develop a single solution to a simple system through trial and error	Can develop solutions with low technical complexity (e.g. Drinking straw tower)	Does not have a social component	Able to address single elements with easily predictable cause and effect relationships	Able to work at a micro scale: individual product, product/ service or service

Fig. 6 Systems design competences and skills matrix. (Illustration by the author)

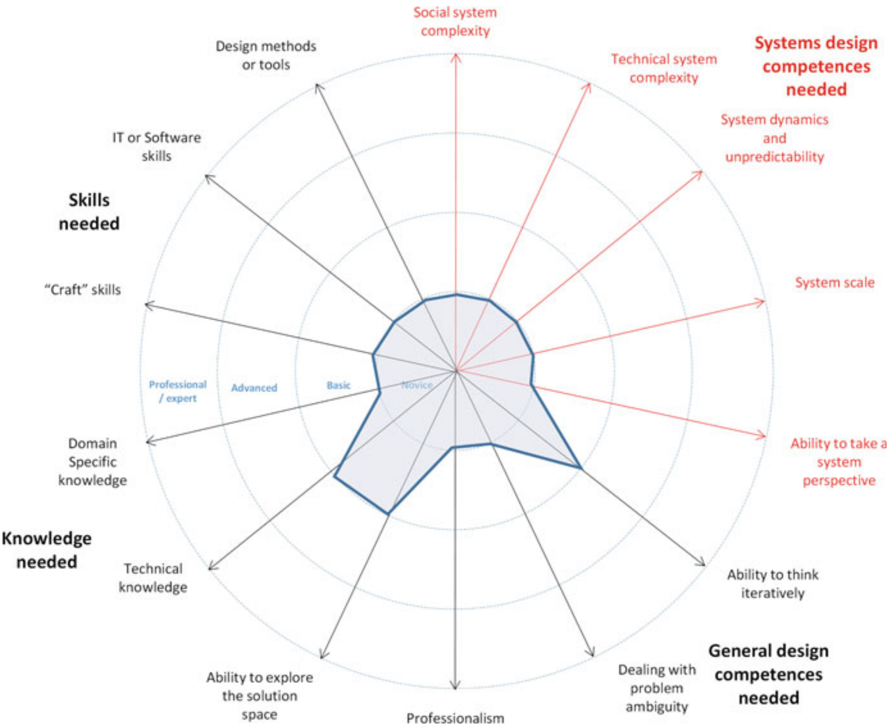

Fig. 7 Design competences for a very basic design task. (Illustration by the author)

ideation, thinking iteratively through trial and error and the ability to explore the whole solution space. Using the system design competences framework, this is illustrated in Fig. 7.

Example 2: King of the Hill

This design brief asks students to create a self-powered (probably battery and motor) vehicle that can scale a ramp and remain at the top, whilst a competitive vehicle seeks to scale a ramp on the other side. This brief is set as a short (1 week) design task at Cambridge University as an introductory design exercise (see Fig. 8). The explicit intention here is to focus on basic machine element design and encourage students to understand the 'fundamentals' of the problem.

Many students will become preoccupied with how they will 'attack' a vehicle that has gained the summit first, or alternatively, how they will defend their position should they be fastest up the slope. Whilst this results in many creative weapons, this becomes meaningless if the vehicle is unable to climb the slope.

The fundamental design challenge (and it is a tricky one) is all about translating the power from the drive system to gain traction up the slope. This simple design challenge also allows the students to gain experience in basic prototyping and the

Fig. 8 King of the Hill. (Photo by the author)

iterative nature of design. As a team design exercise, there is also a moderate element of professionalism in terms of coordinating activities. This simple design problem challenges students technically, but there is little concern for wider system-design challenges (Fig. 9).

Example 3: Product Redesign

In this design brief, students are asked to redesign a simple electro-mechanical product, such as a card-shuffler or electric vegetable peeler. Their starting point is an existing product and they are asked to redesign it to improve its 'value' and so might improve it from a design for manufacturing and assembly perspective in addition to addressing its form, aesthetics, ergonomics and branding. This brief is given to 3rd year Manufacturing Engineering students at Cambridge University.

The brief is slightly more ambiguous as it is for the students themselves to determine how best to tackle the project. They are also expected to use and develop their CAD skills, sketching skills and present their work in a formalised design portfolio. Thus, they need to apply their technical knowledge about manufacturing processes, to show their ability to explore a larger solution space, and to think iteratively and divergently. They are now further seeing that they are intervening, altering, rather than designing from scratch; hence, ripple effects have to be considered. A core deliverable of the project is a detailed design for assembly analysis before and after redesign (Figs. 10 and 11). In this example, the students have simplified the design to reduce part count from 73 to 22 parts and have more than halved the number of assembly steps. This is a project in which the product can be viewed as a small 'system' comprised of subsystems. The scale of the product is small as is the complexity, but there remains some integration of the electrical and mechanical elements (Fig. 12).

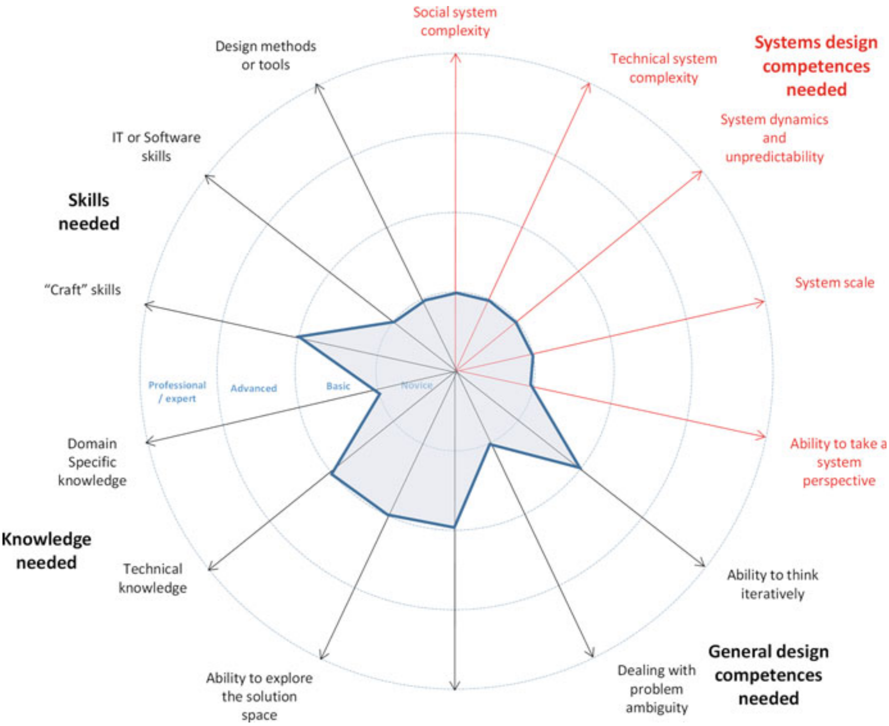

Fig. 9 Design competences for 'King of the Hill.' (Illustration by the author)

Example 4: Capstone Design Projects

Many engineering programmes culminate with a group 'capstone' design project which runs through the whole academic year. The scope of the project is typically very open, and in this example, the brief is typically very broad (e.g. 'a novel manufacturing process' or 'manufacturing a better world') and it is left to the student teams to interpret these statements. There are multiple deliverables throughout the year and by the end of the exercise, students are expected to produce working prototypes, deliver a full design portfolio, produce a business or investment plan and to present their project at a design show. A significant component of the project is learning to work as a team of several students. The most challenging phase is the initial period in which the teams determine exactly what their project will be. To facilitate this, often, an 'ideas fair' is run at which ideas are shared and the students have regular (weekly) consultations with staff.

Depending upon the nature of the project chosen, it is possible for the students to work on projects which are highly complex from a systems perspective, either regarding the technology or the social setting. Four examples from final year Manufacturing Engineering student projects at the University of Cambridge are described below:

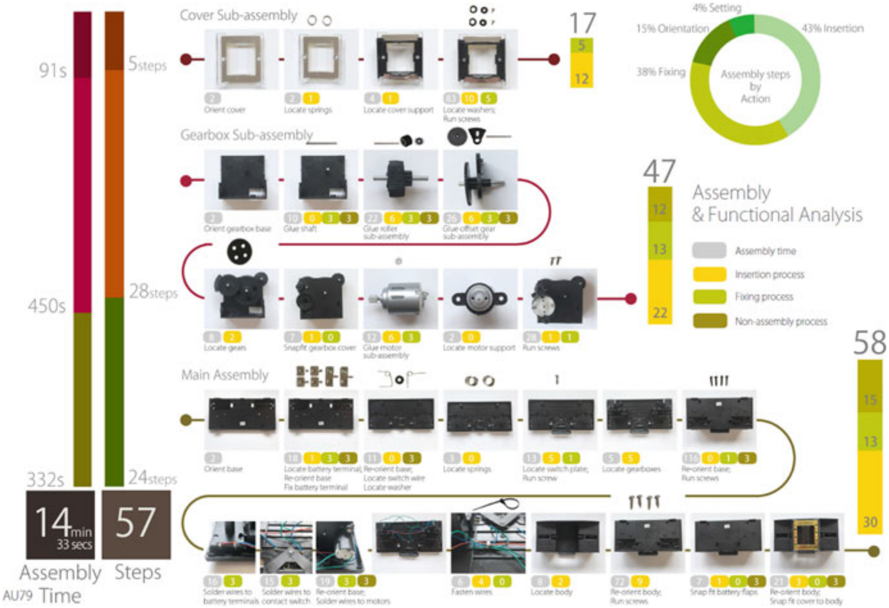

Fig. 10 Design for assembly analysis of a card shuffler before redesign. (Image from the author)

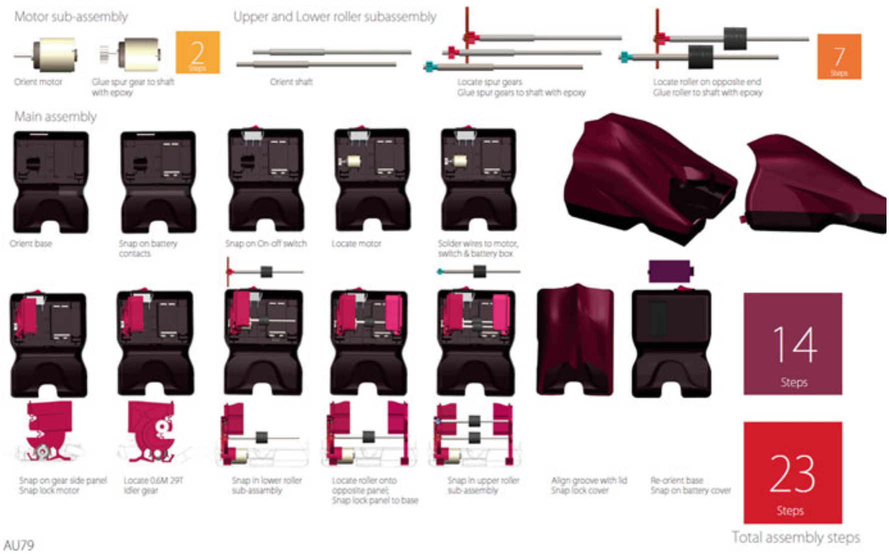

Fig. 11 Design for assembly analysis of a card shuffler after redesign. (Image from the author)

- **Bottlebrick**: a project to repurpose waste plastic bottles for use as bricks for building structures in low-resource settings (Fig. 13). The technical component involved determining a means by which the bottle can be re-formed to create a

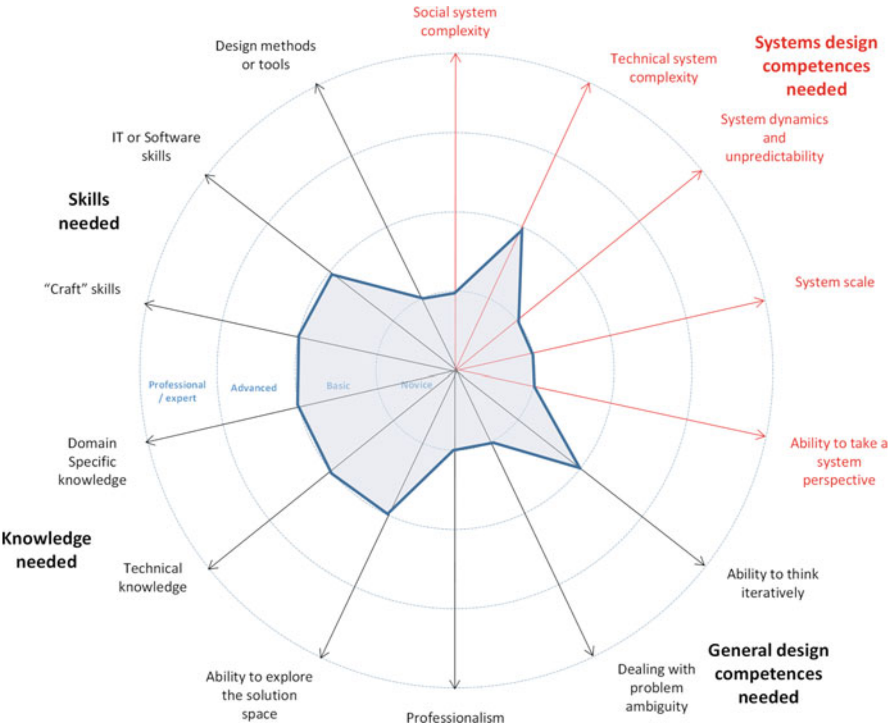

Fig. 12 System design competences for the card shuffler. (Illustration by the author)

tessellating shape, using resources that might typically be available in the intended setting. The broader social system relates to how this might be used in the intended setting and the skills available to produce sufficient bricks to be useful. Whilst developing this, the team discussed their design with charitable organisations and development agencies.

- **Speedsmart**: An innovative approach to incentivising drivers to not speed. The students devised a system in which a speed sensor is linked firstly to a visual warning and then secondly to a traffic light. On detecting a speeding vehicle, the traffic light turns red so that the car must stop (Fig. 14). The time before the light turns to green is dependent upon the excess speed. Failing to stop at the light is also a traffic offence. The team that devised this approach gave careful consideration to the human and behavioural side of the system. They prototyped it and tested it on an unadopted road. The feasibility of the device is dependent upon the technology working but also on the ability to influence a complex socio-economic and political system.
- **Solar oven**: A project to develop a solar oven for equatorial Africa. The solution is designed to utilise locally available resources wherever possible, with as few elements as possible needing to be supplied from overseas. The oven proved to be technically capable of baking at over 200 degrees in the UK summer and a simplified version of the oven was subsequently implemented in Africa. In

Fig. 13 Bottle brick. (Image from the author)

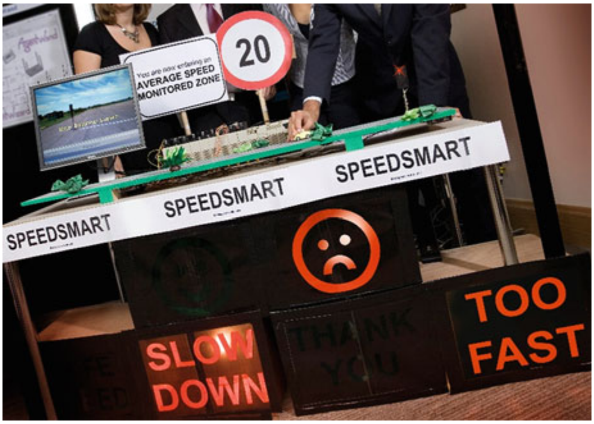

Fig. 14 Speedsmart. (Image from the author)

translating the design for actual use, further simplifications were made in response to the availability of skills and materials locally. These insights were not available to the team during the project and instead they needed to base their decisions on the best insights they had available through charitable organisations and talking with aid workers (Fig. 15).

These three examples give a sense of the nature of typical projects. Some have greater technical complexity, some deal with more significant challenges relating to the wider social system of use. The nature of the design brief as a result is much less constrained across all dimensions (Fig. 16), with students inherently dealing with far higher levels of ambiguity to create systems with a larger scale and greater technical complexity. However, it is likely that the scale is still limited to a product within a larger social setting. Few of the projects are seeking to address a much larger and more complex social system. Students need to draw on a more advanced set of

Fig. 15 Solar oven. (Image from the author)

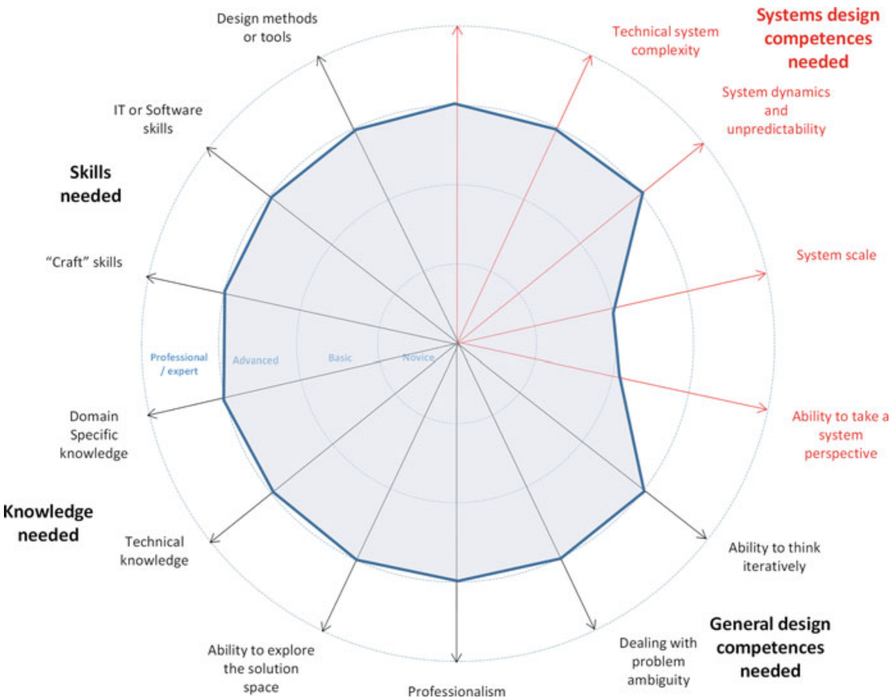

Fig. 16 System design competences for the capstone design project. (Illustration by the author)

design skills and apply their engineering knowledge to new problems. They also need more advanced professional skills, learning to manage their team in a high-pressure environment.

Example 5: Major Systemic Transformation

Students across DTU, the Technical University of Denmark, e.g. in the master's course Holistic Design of Engineering Systems, tackle team based projects to address a major challenge such as digital transformation, healthy and inclusive societies, and sustainable futures. Application domains include inter alia health and care, food, energy, infrastructure, water.

The students are asked to on the one hand go through a system design process from analysis, to development, to evaluation and on the other hand to do that on three concurrent system levels: the artefact as product or service; the complex system as the context where the artefact is implemented; and at the engineering system level, including regulations, national and international contexts, etc.

The first tasks are to investigate and potentially question the problem brief, to scope the project and also to get to the bottom of what is really needed. Initially, students are encouraged to be inquisitive towards 'in what way might we' and be solution-agnostic. In analysing the current situation, activities include: the demarcation of the system (an ongoing activity throughout the project); establishing problem boundaries; and mapping out the area of investigation, the area of solution, the area of intervention and the area of effect. Emphasis is placed on the connections between the elements in a system and thereby the trajectory of potential knock-on effects when intervening by design.

For each project, students are asked to be explicit about the underlying design principles they are endorsing, i.e. the worldview, the problem-solving process they are using as inspiration, i.e. the design process, the life cycle stage they are intervening in, and finally the methods they are using when designing and when interacting with the multiple stakeholders throughout the system design process. Solutions do not necessarily depend upon the creation of a 'technical' component, although a technical or tangible component might take the role of an enabler to a wider system solution.

To identify projects, students are encouraged to form their own projects and additionally, the course works closely with a range of partners, including industrial, governmental, and charitable stakeholders, with large organisations and start-ups, and with initiatives such as DTU Skylab in partnership with Students Hack Folkemødet http://www.hackfolkemodet.dk/solutions-2019/. Folkemødet is a nation-wide citizen festival devoted to participatory dialogue for societal stakeholders, taking place annually at the island of Bornholm. The problem briefs given by a client partner to the student group are inherently broad (e.g. develop and test solutions facilitating involvement in Denmark's Mission 70% C02 reduction or develop and test solutions to encourage festival stakeholders to manage waste, show us how to engage coffee-drinking festival guests in contributing to our ambition of 100% recycling). The students take the role of system design consultants and are asked to develop innovative solutions targeting specific sustainability challenges.

As an example, one of the projects addressed the challenge that people are not aware about the social and environmental benefits of sustainable coffee. The design goal the students then formulated was to create awareness about sustainable coffee and the Sustainable Development Goal (SDG12) of Sustainable Consumption and Production, by activating, informing and engaging consumers age 20–30 in an event setting. This has led to the solution Kaffetræet (The Coffee Tree) as a gamified way of creating awareness about certified coffee and its positive impacts on coffee production and consumption. It symbolises the hard work it takes for a coffee farmer to pluck 100 beans for one cup of coffee (Figs. 17 and 18). On the back of the artefact, there are flaps with factual information about organic farming, certifications, the coffee industry, water use, the supply chain, and more. This information has, through testing of the prototype, proven that people get a reaction of disbelief resulting in them leaning towards buying certified coffee in the future.

On the artefact level, the prototype informs, engages and activates the festival goers and communicates ways for sustainable coffee production and consumption.

Fig. 17 Prototype testing for sustainable coffee concepts. (Image from http://www.hackfolkemodet.dk/circle-solutions-kaffetraeet/)

Fig. 18 Prototype testing for sustainable coffee concepts. (Image from http://www.hackfolkemodet.dk/circle-solutions-kaffetraeet/)

On the wider complex system level, early outcomes are impact on the coffee manufacturer as client to re-think their strategic initiatives and their interaction with certification standards and the farmers from where the beans are sourced. On the wider engineering systems level, the manufacturer is now working more closely with regulators on increased adoption of good agricultural practices that interfaces with circular resource practices more widely, including people, water, energy, biodiversity.

One of the challenges in projects which are genuinely systemic is prototyping. Where problems are cross boundary, large, complex, have multiple stakeholders, etc. one has to be creative in looking at ways of prototyping. Physical prototyping may work for some activities and levels, system modelling, alternative journey mapping, what-if scenario forecasting may all be ways to engage stakeholders in the systemic effects of an intervention and the creation of a new situation that is itself evolving and dynamic going forward.

Tackling a problem of this scope requires engagement with a highly complex socio-technical system, where the system may be unpredictable, is of a large scale and students inherently need to take a broad systems perspective (Fig. 19). In Fig. 19, the dotted line suggests that it is possible for students to stretch the boundary of the project, depending on the specific needs of the project.

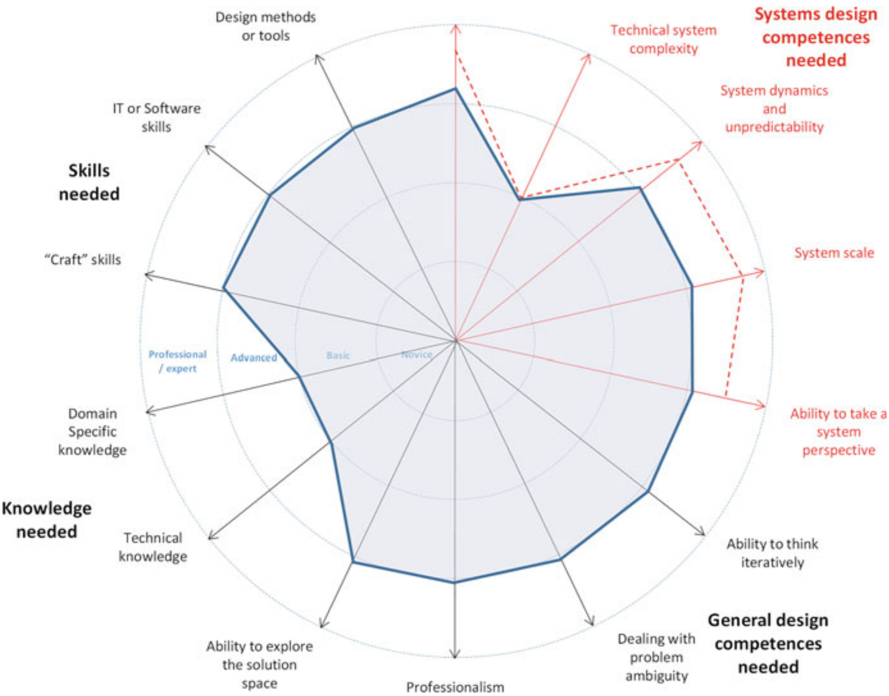

Fig. 19 System design competences for a systemic transformation project. (Illustration by the author)

Using the Matrix at a Programme Level

By considering any design project as being bounded by a series of constraints, it is possible to ask further questions about how system design knowledge, skills and competences are developed.

In a paper describing engineering design education at the US Coast Guard Academy, Wilczynski and Douglas (1995) describe how in their first year, students tackle ‘small-scale’ design problems before progressing to broader system design projects in later years. The earlier ‘small-scale’ problems often relate to engineering challenges to help in understanding and applying engineering theory (e.g. the construction of paper-beams, stress/strain and free body diagrams). More open-ended problems are then introduced before concluding with a capstone project which is inherently more open ended. This approach seeks to treat engineering design as a sequential learning process.

This example shows a classic engineering design education progression from multiple tightly focused and highly constrained projects, through to projects that are larger in scale and complexity and that have significantly fewer constraints (Fig. 20). Of specific note, it is not unusual in engineering programmes for the scope of the system to grow as the course progresses.

However, there are many ways in which this progression might be planned and clear question marks about whether competence in all areas necessarily develop in unison? For example, it is quite feasible to develop some basic competences whilst

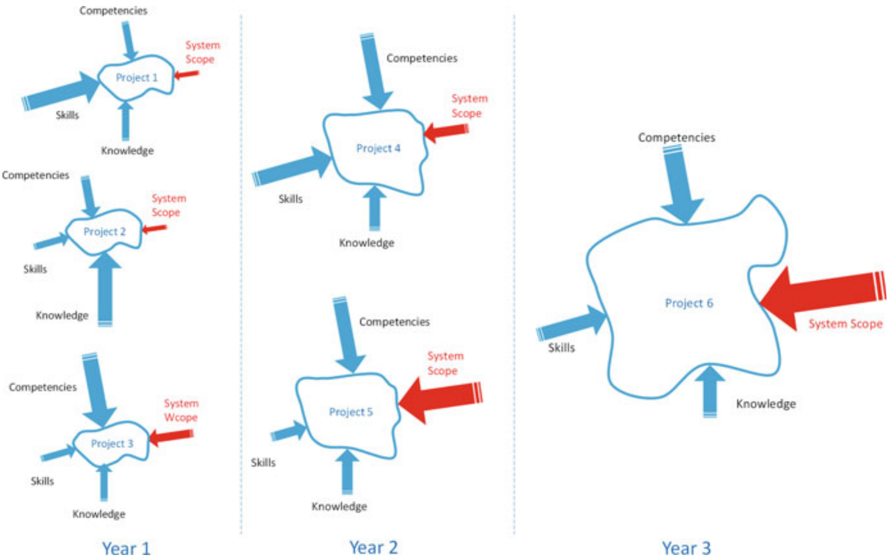

Fig. 20 How might a design curriculum evolve through a design course? (Illustration by the author)

working on simple systems. At the same time, is it possible to design complex socio-technical systems without first acquiring high levels of sketching ability?

Telenko et al. (2014) provides multiple example projects, to demonstrate how considering different system boundaries can be beneficial, from technical sub-systems, the integrated technical system as a whole and the socio-technical system in which the designed artefact operates. Telenko proposes the use of *designettes*: short design activities which seek to teach fundamental engineering principles in a design centric or project based manner. Each small project has a specific and delineated set of learning objectives, which are comprised of 6 generic sets of learning objectives for the design of systems (these are paraphrased):

1. Engineering subject fundamentals: applying knowledge of maths/physics, etc.
2. Recognising problems and opportunities: through reflection, observation and developing hypotheses
3. Assessing contexts, opportunities and needs: user, market and background research
4. Ideate, abstract and represent: recognising and making analogies, develop models and generate concepts
5. Decision making under uncertainty: using inductive and deductive reasoning
6. Utilise available resources within a complex system: including systems thinking

These designettes *"structurally provide open-ended problems and anchors for linking ideation techniques and methods within an engineering context."* (Telenko et al. 2014, p. 3).

By clearly articulating the expected skills and competences to be demonstrated in a specific project, it is also possible to assess whether or not these have been demonstrated and to what level of ability. Thus, if a project requires a student to demonstrate an 'advanced' level of 'craft skills', then this can be evaluated explicitly in any subsequent assessment. This is consistent with an approach proposed by Shah (2005) to evaluate the acquired skills of students (as opposed to assessing the outputs of the project itself). The implication is that each design exercise is explicit about the intended skills development. Thus, it is the demonstration of acquired skills that are graded, rather than the design process or the design outcome.

Telenko indicates that each assignment is designed with the *"objective of teaching, practicing and assessing a particular sub-set of skills."* (p. 8). Specific skills described include: Creativity, Lateral thinking, Imagination, Drawing ability, Visual thinking, Problem definition and Analysis. Shah provides a range of design briefs which each articulate the specific skills being developed and assessed. These problems are interesting as they place clearly defined boundaries around each design problem.

Further study is needed to better understand the different ways in which a series of projects might best be configured. There are evident advantages in taking a step-by-step approach to developing competences. However, there might also be advantages to exposing students to more complex problems sooner so that awareness and skills develop earlier.

Conclusions

This chapter has provided an overview of thinking and research related to educating systems design engineers, with a particular focus on the pressing need to pay attention to complex socio-technical engineering systems problems. Thinking has progressed since the 1980s where systems were mostly viewed as comprising multiple technical sub-systems, with a ‘tight’ boundary around the product. Today, there is a pressing need to tackle complex global challenges, requiring engineers that are comfortable in dealing with complexity, ambiguity and socio-technical engineering systems that have multiple stakeholders with different needs. Many design educators are calling for action to ensure that the next generation of engineering designers are equipped to tackle these problems.

Indeed, we can view the design of engineering design education itself as a complex socio-technical engineering systems problem. To help navigate this systems complexity, a ‘systems design competences and skills matrix’ has been introduced. This tool aims to help design educators be explicit about the boundaries for any project, but more importantly, to consider how design projects delivered over a whole programme are planned to help students build holistic competences, skills and outlook.

Cross-References

► Choosing Effective Means: Awareness of Bias in the Selection of Methods and Tools
► Digitalisation of Society
► Engineering Systems Interventions in Practice: Cases from Healthcare and Transport
► Formulating Engineering Systems Requirements
► History of Engineering Systems Design Research and Practice
► Properties of Engineering Systems
► Roles and Skills of Engineering Systems Designers
► Sustainable Futures from an Engineering Systems Perspective
► Transforming Engineering Systems: Learnings from Organising Megaprojects
► Transitioning to Sustainable Engineering Systems

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Engineering Systems Interventions in Practice: Cases from Healthcare and Transport

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Christian Thuesen, Igor Kozine, Anja Maier, and Josef Oehmen

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C. Thuesen (✉) · J. Oehmen
Department of Technology, Management and Economics, DTU-Technical University of Denmark, Kongens Lyngby, Denmark
e-mail: chth@dtu.dk; jooehm@dtu.dk

I. Kozine
Department of Technology, Management and Economics, DTU-Technical University of Denmark, Kongens Lyngby, Denmark

Southern University of Denmark, Odense, Denmark
e-mail: igko@health.sdu.dk

A. Maier
Department of Technology, Management and Economics, DTU-Technical University of Denmark, Kongens Lyngby, Denmark

Department of Design, Manufacturing and Engineering Management, University of Strathclyde, Glasgow, UK
e-mail: amai@dtu.dk

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Abstract

This chapter presents four cases of practical interventions in engineering systems: transforming national healthcare by construction of super hospitals; developing deep emergency response using AI; decarbonising global shipping in a global system transformation; and prototyping future urban transport systems. The cases come from two sectors, healthcare and transport, and demonstrate interventions of various complexities and lifecycles. To ensure comparability, each case is developed based on a common analytical framework and in-depth interviews with leading practitioners working on transforming engineering systems. Findings across the cases document five learning points. Engineering systems design does: firstly, apply a systems perspective to understand the entanglement of different system elements, their connections, boundaries, and causal effects; secondly, evaluate the value of these systems in the light of current performance, state of play, (future) technological possibilities, and user needs to identify complication and societal business cases for interventions; thirdly, organise a lineage of projects and programmes across time and space for systematised experimentation to explore the solutions space and implementation at different levels in the engineering system; fourthly, embed standardisation and flexibility in the system for maintaining value delivery while embracing future needs and opportunities; and finally, carefully navigate the complex and dynamic stakeholder landscapes, manage, and develop the discourse within and around the systems through user and public engagement to ensure benefit realisation of the intervention.

Keywords

Construction · Emergency response · Engineering systems design · Healthcare · Transport · Shipping · Self-driving vehicles

Introduction

The present handbook demonstrates various theoretical and conceptual frameworks for designing engineering systems through interventions. This chapter is dedicated to exploring the practical sides of designing engineering systems. Our ambition is not to “pin down” best practices of engineering systems design but to present vivid cases that stimulate reflections and learning across different types of systems, sectors, or professions.

We have identified four cases we find particularly relevant as they illustrate the diversity of practices and scale. Each case is based on semi-structured interviews conducted by a researcher in the engineering systems domain with a leading figure in industry, government, and from a non-governmental organisation, around core engineering systems design challenges. Given the context, researcher, and availability of material, cases vary in length (Fig. 1).

The cases present a practitioners’ view on specific engineering systems design challenges and practices. In this process, we use the following simple mode outlined in Fig. 2 for engineering system design inspired by Züst and Troxler’s (2006) framework for systematic problem-solving. Based on the current situation and state of play at the system level, specific trends, trigger events, and challenges create a complication and a case for intervention, including the definition of goals. Subsequently, the solutions are developed and implemented, impacting the system and starting a new state of play. We use this framework for the case analysis. The detailed structure of the cases is outlined in the breakout box.

Breakout Box: The Structure of the Presented Cases

- **Introduction to the engineering system** presents the engineering systems and role in society.
- **Situation** outlines the historical development and context for the current challenge.
- **Complication** illustrates the current configuration of challenges and the identified goals for the intervention.
- **Solution** stipulates the specific intervention and the broader organisation of actions in the solution development process.
- **Implication** summarises the anticipated and actual consequences of the interventions.
- **Reflections and conclusion** identifies core learning points from the case.

Fig. 1 Four cases exploring engineering systems design in healthcare and transport. (Pictures from Rådgivergruppen DNU, Slawos, CEMS, Ulrik Jantzen, used with permission)

Central Features of Engineering Systems Design

The cases illustrate the multifacetedness of engineering system design. The cases show heterogeneity and also identify common challenges and shared practices in engineering systems design. The cases are presented based on the framework introduced above, see Fig. 2 and summarised in Table 1.

Understanding and Governing the System

A prerequisite for managing engineering systems and potential interventions is a thorough understanding of how they work as a system and how they are influenced and influencing other connected systems. The development of healthcare services is dependent on the emergency response systems, which again is dependent on the transportation infrastructure. The dependency on other systems makes it essential to define the boundaries of the systems, which along with an understanding of the engineering systems' core sociotechnical properties and user experiences, makes it possible to understand the system's performance.

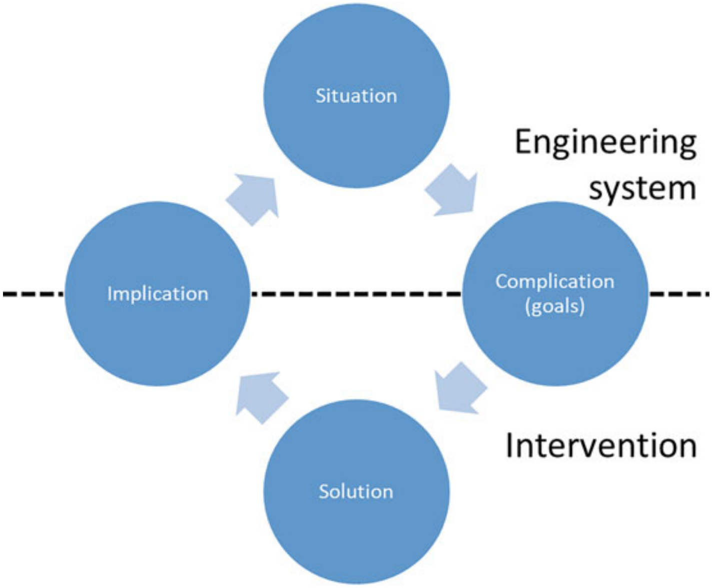

Fig. 2 A framework for engineering systems design

A wide range of indicators and metrics monitor the performance of the systems. This includes capacity measures like number of beds and CT scanners (hospitals), number of cars (transport), ambulances (emergency response), and ships (shipping). The performance of a system is also measured by output metrics such as number of treatments (healthcare), emergency missions (emergency response), number of passengers (transport), and freight (shipping). The indicators and metrics create transparency around the systems' performance and make it possible to evaluate trends over time and benchmark individual systems. This could include subsystems like the performance of a particular hospital or the whole system's general performance, making the comparison between regions and even countries possible. A similar logic applies in the shipping case where metrics of the individual ships can be aggregated to the portfolio level in the form of the shipping company's fleet and the global shipping industry. This ability to qualify and quantify the performance of the engineering systems is crucial in the cases. It is vital for decision-makers in establishing the (societal) business cases for the location of the hospitals or de-risking investments in zero-emission ships. It also plays an essential role in running research-supported innovation processes like the implementation of AI in emergency response.

Besides understanding how the engineering systems work, the past and current performance of the system, insights into emerging technologies, societal trends, and other future perspectives are essential for evaluating and adjusting the systems current and future relevancy. New emerging trends and technologies create opportunities and threats, which could disrupt the engineering system. Some of these are specific for a system like an ageing population (healthcare) or fuel prices (shipping),

Table 1 Case overview: systems characteristics, intervention, complication, solution, and implications

Case	Transforming national healthcare	Developing deep emergency response	Decarbonising global shipping	Prototyping future urban transport
Sector	Healthcare/ hospitals	Healthcare/ emergency response	Transport/ shipping	Transport/self-driving vehicles
Targeted SDGs	3	3	13	11
People affected *Purpose*	5,7 million	1,8 M +1,2 million calls and 600.000 missions a year	The population of the world? 80% of global trade	+1,5 million
People involved *Social complexity*	100.000 employees including doctors, nurses GP, hospitals, specialists, policymakers	Employed in the call centres Ambulance crews 25.000 heartrunners	Ship designers, shipyards, owners, operators, customers, port operators Hundreds of different legal and regulatory environments	6.000 users and employees of hospitals, industrial areas, campuses
Physical infrastructure *Technical complexity*	56 hospitals 3,8 million m^2 15.000 beds	47 emergency response units 25 ambulances with 24-h activity 7.060 automated external defibrillator (AED)	70.000 merchant ships 1.000 major ports	1 bus 4 bus stops 375 m route
Long lifecycles *Uncertainty*	100+ years	10–15 years	20–30 years	3–5 years
Intervention				
Duration	20–30 years	5–15 years?	10–20 years?	5 years?
Driver of change	(Mega) programmes in regions	Programme of innovation projects	Programme in a world-leading business	Exploratory projects
Scale of change	Top-down system reconfiguration	Bottom-up innovation based on data	Middle-up-down system reconfiguration	Bottom-up prototyping of solutions
Levels involved	Government → regions → hospitals	EMS → regions → global community	Business → global community → government	Buses → hospitals → cities

(continued)

Table 1 (continued)

Case	Transforming national healthcare	Developing deep emergency response	Decarbonising global shipping	Prototyping future urban transport
Perspective	Politician	Professional	Professional	Politician-professional
Complication (goals)	An inefficient healthcare system focusing on hospitalisation rather than treatment. Enforced by old, outdated buildings and practices Goals: Improved healthcare services	Of 130.000 emergency calls per year, 1–2% are out-of-hospital cardiac arrests (OHCA) Goals: Better response time and accurate detection of OHCA, safe lives	Shipping alone accounts for 3% of the global CO_2 emissions. Emissions are expected to increase 250% until 2050 in a do-nothing scenario Goal: "infuse confidence to act in time"	Increasing pollution (high air pollution and CO_2, noise, etc.). Immature technology, ethical issues, behaviour change, legislation, lack of investment Goals: (e.g. sustainability, equity, etc.)
Solution	Centralisation of treatments and specialisation by the construction of super hospitals and closing of regional hospitals	System innovation through technology intervention using artificial intelligence (AI) to support dispatch	Make low-carbon or zero-carbon propulsion options a viable and attractive choice for investors through de-risking, technology development, industry leadership, and regulation	Solution (mixed transportation means with a significant share of autonomous public transport). Attracting big bus making companies and investors for running tests
Implications	Radically transformed healthcare system realising an increasing output (treatment) – local resistance and challenging organisational change processes	The machine learning framework was significantly faster than medical dispatchers in recognising OHCA, albeit with a lower positive predictive value Spin-off: Resilience for covid pandemic	Building trust in a global stakeholder community around the decarbonisation agenda	Redefining public space in cities, change of behaviour, healthier and greener cities

while others are relevant for a broader set of systems. For instance, the ongoing urbanisation influence both healthcare and transport in the form of changing population around existing hospitals and increased congestion on roads and in public transportation. As a technological parallel, artificial intelligence (AI) offers value-added services like decision support for emergency response and self-driving vehicles.

The systems themselves are embedded in regulatory and political frameworks. They are governed by laws as exemplified in the healthcare act and supported by standards like autonomous vehicles. Depending on the cultural context, the systems are configured in a mix of public or private activities. In a Danish context, the healthcare system is a public service provided by the government-financed through taxes. In contrast, are the transportation system, to a more considerable degree, run by private entities. In any situation, the long lifecycles of the systems require collaboration between different stakeholder groups and political parties aligning interests over a long period. This form of cooperative government is a crucial feature of Danish society, as exemplified by the collaboration between the right and left parts of the political spectrum in transforming the healthcare system. The continuous dialogue between various stakeholder groups and their interest organisations creates a political landscape around the engineering systems that must be navigated in transforming the systems. This is also found in the shipping case, although the context is different. The global nature of trade makes the shipping system far less regulated and based on global market dynamics. However, the solution is still centred around aligning influential stakeholders in the form of shipping business towards a shared goal on global reductions CO_2 emissions. This enforces collaboration between the industry and governmental bodies almost in the form of a public-private partnership.

Formulating the Complication (Goal Setting)

The cases demonstrate how engineering systems are developed through generations providing value to society in the form of healthcare or mobility. While the systems gradually respond to changing user behaviour and technological trends, they can only do so to a certain extent. However, societal change, technologies, and trends offset the value the system provides with users' emergent needs and stakeholders' interests. Thus, the system might get "out of sync," enforcing obsolete practices like hospitalisation and undesired user behaviour like increasing private motoring or global trade. The systems cannot be left ungoverned but must be carefully regulated and re-engineered to ensure relevancy and efficiency. This creates the complication (societal business case) for engineering systems interventions.

The cases of the four interventions illustrate different scales and uncertainty around the complication. All cases depart in broad societal engineering systems and the engrained sociotechnical complexity frame the specific intervention at different scales. The shipping case takes a global perspective, the hospital case a national perspective, and the transport case takes a local and exploratory one. This is not found in the nature of the engineering systems but rather in the temporal dimension and the proposed solutions. The challenges of the healthcare systems have existed for years, just as the transport systems issues with congestion and pollution, but the scope of the interventions is different. While the super hospitals transform the whole sector, the transport case only explores and matures technologies around autonomous vehicles in the form of busses. However, these small interventions might have implications in a broader setting, like when the research in emergency medical services in the city of Copenhagen, Denmark, inspires the global community to change practices in other countries.

In the cases, a substantial amount of analysis drives the initiation of the interventions. This includes information on the usages of the systems, current demographics, systems productivity, sustainability metrics, available technologies, etc. The cases for interventions should not be seen as discrete decisions at a time but rather as a process in the form of myriad decisions constituting complication and affiliated solutions. The transformation of the healthcare system through hospitals and emergency response relied on a range of decisions, gradually defining the complication and solutions in the process. This is also taking place in the Mærsk Mc-Kinney Møller Center, where decisions systematically are de-risked towards zero-carbon shipping. This suggests that the design practices of engineering systems exhibit a goal-seeking behaviour where specific objectives gradually mature.

Identifying and Developing Solutions

The open-ended characteristics of the problems and long lifecycles of the engineering systems suggest that transformation is building on a series of projects at various system levels. While the overall objectives might be specific, such as improving healthcare and reduction of congestion and climate impact, the paths to achieve these objectives are multiple and uncertain given the developing technological possibilities, societal trends, interest of stakeholders, and regulatory frameworks.

This suggests that systems' change is achieved not only by single large-scale projects but also through different temporal and spatial configurations of projects and programmes. The testing of autonomous busses organises four projects separated in time and space with increasing complexity. They started in a hospital setting, moving to an industrial area, a campus, and lastly, at the city level. This organisation seeks to establish a learning process that creates a foundation of *"evidence-based knowledge and hands-on operational experience to ensure public transportation will play an important part in a future self-driving transport system"* (Bergendorf 2019). The construction of the super hospitals also organises projects in time and space but in a different way. The projects (hospitals) are carefully situated in the Danish Regions, taking population, healthcare services, and existing infrastructure into consideration. However, compared to the serial nature of the transport case, the temporal organisation of the hospitals is of a parallel nature. This suggests the existence of different modes for engineering system interventions: a mode for exploration of the solution space and a mode for comprehensive implementation of solutions simultaneously in the system. While the first mode focuses on prototyping solutions, not directly impacting the engineering system, the other fundamentally transforms the sociotechnical fabric of the engineering system. The two modes might be linked in time, as implementation requires well-developed solutions, which is projected to have the desired effects at the systems level.

Different levels of the engineering systems also constitute critical linkages between various projects and programmes. While the realisation of super hospitals seems like the essential part of the intervention of the healthcare system, it could not have been achieved in the old regional and municipal context. The reconfiguration of the regional governmental landscape is a core prerequisite for enabling the benefits of the constructed super hospitals. This illustrates the sheer size of the transformation. Transforming the engineering system is not just about changing the system's local sociotechnical fabric but also the political structure that governs it. While this was not the case for implementing AI in emergency response, it will be a requirement for shaping the future market for global trade.

Technologies play an important role in the intervention in engineering systems. AI is central in supporting the decision-making in the emergency response case and the self-driving busses in the transportation case. However, the technology is not always high-tech, as illustrated in the super hospital case where the practices are changed by reconfiguring technology from "passive" bedrooms to flexible treatment rooms with machinery supporting the production flow like CT scanners.

Working with technology as a part of the intervention, one must consider the variance in the lifecycle of different technologies and the overall lifecycle of the engineering system. This is explicitly identified in the long lifecycle of the ships and hospitals. Some embedded technologies such as ships, buildings, and infrastructure exist for decades while others, like CT scanners, change every 5 years. What is more, the technology enforces system structures, creating path dependencies, which stimulates certain practices and systems behaviours over others. The physical location of the hospitals enforces a centralisation of treatments ensuring the necessary population for developing and maintaining specialisations. These structures are essential for driving the performance of the engineering system in a specific direction. However, the design should not be too rigid as the practices should adapt to future possibilities given by technological development and societal trends. This is achieved in the healthcare case by making the treatment rooms flexible to accommodate changes in treatments and reorganising specialities between hospitals.

Managing Implications (Realising Benefits)

While technology plays a vital role in the interventions, it is at the end of the day people making the systems work and requesting the services provided by the system. As consumers, patients, and commuters, they are why the shipping system, healthcare system, and public transportation exist. In addition, as employees in ports, hospitals, emergency centres, and bus companies, they are crucial for delivering goods, healthcare, and public transportation. Changing these systems cannot be achieved without considering the consequences for people in and around them. A substantial part of designing engineering systems must handle users and stakeholders influenced by and influencing the intervention. Here the cases document two central practices: user-driven design and stakeholder engagement.

Co-design is crucial in prototyping the solutions of the interventions to ensure acceptance and effectiveness of the solution. In the transport case, user feedback on the autonomous system was central in gaining knowledge about the user behaviour and needs. Similarly, user involvement in patient and treatment rooms was pivotal for developing detailed hospital design, which could meet the requirements for efficient healthcare processes. While the involvement has proven valuable in both cases, it is challenged by the long duration of the intervention. Although the hospitals are built in parallel, they are still spread out throughout 10 years. Similar are autonomous busses not introduced overnight but through an extended period.

Consequently, the knowledge created in the user engagement might be obsolete when the system is ready to launch. This was the case in one of the hospital projects where the user-designed treatment processes proved very difficult to follow in real-life situations. Further difficulties in moving hospital functions from one location to another suggest that organisational change practices and resources should follow engineering system interventions.

Stakeholder management is essential in the cases of the fundamental transformation of the systems. Building new city-based hospitals with more than 4.000 jobs while closing several hospitals in the countryside cannot be realised without careful management of public perceptions. Interventions will have negative consequences; some might lose their jobs, and others might get longer distances from the nearest emergency hospital. In addition, interventions might require tough decisions that may have negative consequences in the short term to achieve long-term benefits like moving the functions of a hospital. Given these challenges, interventions must be supported by collaborative processes and policies, ensuring long-term stability for realising the societal benefits of the engineering system.

The societal benefits of the engineering systems interventions are profound. At various levels, they hold the key to the sustainable transformation of our societies. Although none of the cases explicitly address the sustainable development goals, they make substantial contributions to realising SDG3 Good health and well-being through super hospitals and deep emergency response, SDG11 Sustainable cities and communities by prototyping future urban transport systems, and SDG13 Climate action in decarbonising global shipping. The cases thus document the centrality of engineering systems interventions in developing sustainable societies.

Concluding Notes

The cases demonstrate how interventions happen in practice. From the individual cases, we have identified the following learning points for engineering systems design:

1. Apply a systems perspective to understand the entanglement of different system elements, their connections, boundaries, and causal effects.
2. Evaluate the value of these systems in the light of current performance, state of play, (future) technological possibilities, and user needs to identify complication and societal business cases for interventions.
3. Organise a lineage of projects and programmes across time and space for (1) systematised experimentation to explore the solutions space and (2) implementation at different levels in the engineering system.
4. Embed standardisation and flexibility in the system for maintaining value delivery while embracing future needs and opportunities.
5. Carefully navigate the complex and dynamic stakeholder landscapes, manage and develop the discourse within and around the systems through user and public engagement to ensure benefit realisation of the intervention.

The cases present a selection of engineering systems. The examples highlight different aspects of designing such highly complex and uncertain systems supporting our modern lives. Thus, this is a call to action for you, for us all to continue the exploration of demonstrator cases in engineering systems design.

Case 1: Transforming National Healthcare by the Construction of Super Hospitals

A Case on the Centralisation of the Danish Healthcare System – Engineering Healthcare

See Fig. 3.

Fig. 3 The transformation of the Danish healthcare system by the construction of 16 super hospitals. (Picture: Rådgivergruppen DNU, used with permission)

Introduction to the Healthcare Engineering System

Well-functioning healthcare systems are central to modern societies. Targeting every citizen and promoting good health and well-being is pivotal for society's ability to flourish and prosper. Through generations, these systems have evolved based on advancements in medicine and technology influencing and influenced by the greater societal development like ageing and urbanisation – the following graphs document recent changes of healthcare systems in a subset of European countries. The radical reduction in available beds and increased CT scanners demonstrates a paradigm shift in the underlying systems. Over decades, the healthcare system has transformed from a hospitalisation system emphasising the number of beds to a treatment system favouring changing practices and adopting new technologies like CT scanners (Fig. 4).

Transforming these systems is not easy. However, as we will explore, this has been achieved during the last 20 years in Denmark. Our guide is Bent Hansen, the former president of the Danish Regions, responsible for driving the programme of the super hospitals and working with the transformation of healthcare over his 36 years career as a politician.

We here view healthcare as an engineering system – a complex sociotechnical system. The technical side consists of building structures (small and big hospitals), infrastructure (ambulances, helicopters), equipment (CT scanners, etc.), beds, etc. The social side comprises doctors and nurses, GP/hospitals/specialists, regulatory bodies (regions), political systems, interest organisations, and the citizens. Exactly the citizens happen to be the primary social group as they represent the fundamental reason for the existence of the healthcare system. This is documented in the societal purpose formulated in the first section of the Health Act, which is *"to promote the population's health and prevent and treat illness, suffering and disability for the individual"* (Sundhedsloven 2019).

Providing healthcare is thus one of the most critical governmental agendas. It is on top of the political agenda, and at the same time, it represents one of the most significant expenditures in the Danish national budget. Public health expenditures increased from € 18 billion (2007) to € 23 billion (2014), which corresponds to 15,6% of GDP (OECD 2019). The ability to provide high quality and cost-effective healthcare is thus of utmost importance.

Breakout Box: Key Figures of the Danish Healthcare System

- Costs: €23,180 billion. Approx. 15,6% of GDP (OECD 2019)
- Number of operations per year 2018: 2.119.997 (Esundhed 2019)
- Number of diagnoses per year 2018: 1.373.414 (Esundhed 2019)
- Number of employees (FTE) in hospitals: 90.212 in 2001 and 106.676 in 2018 (OECD 2019)
- Number of patients (percent of the population): 38,2 (2002) to 40,3 (2009)

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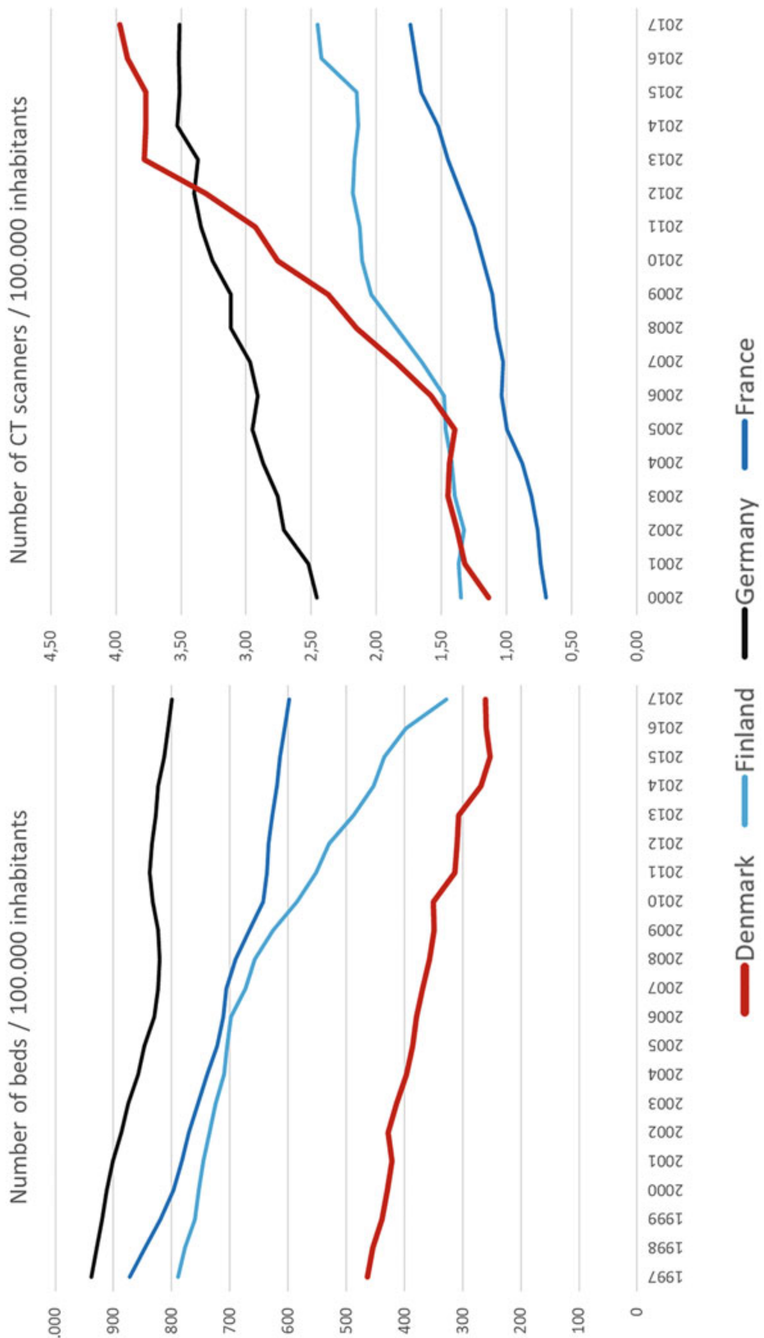

Fig. 4 The paradigm shift in European healthcare systems

- Number of healthcare facilities (small and big): 56 facilities, 3,8 million m^2
- Number of beds: 22.927 in 2001 and 14.429 in 2018 (OECD 2019)
- Equipment: 370 scanners and 60 linear accelerators

Situation: From Hospitalisation to Treatment

One hundred years ago, around World War 1, there were significant investments in hospitals to provide healthcare services to the Danish population based on promising results in medicine. To ensure prompt treatment and hospitalisation, the layout was governed by *"a rule of thumb that you should be able to reach a hospital with a horse-drawn carriage within one hour"* (Hansen 2019). Consequently, many small hospitals were constructed in cities all around the country.

The hospitals represented the core technology by which the local government could deliver healthcare to the citizens. The idea that the patients should stay at the hospital until they were cured guided the hospital design. Therefore most of the space in the hospitals was taken up by large patient rooms featuring multiple beds (up to 8). The general belief was that as long as you got to the hospital, you would be in the best hands – an understanding that was kept alive until the 1970s and 1980s.

Against the backdrop of the flower power revolution, people started questioning institutions and authorities of society, including doctors. A doctor was not just a doctor. The advancement in medicine included a growing specialisation among doctors. One doctor could not master the whole discipline while still pushing the boundaries through new research. Furthermore, doctors at the smaller hospitals carried out an increasing variety of treatments, not always with successful outcomes. While some of the smaller hospitals only completed two surgeries a month for breast cancer, the big hospitals could do more than 100 per month – with a much higher success rate. Bent Hansen explained this in the following way: *"When I started in this business (as a politician). If [a woman] got breast cancer, then there was a 50% chance that she was dead after five years. Today it is less than 10%. Why? Because you come to someone who specialises in the [treatment] and has the necessary equipment."*

Complication: Inefficient Healthcare Services Enforced by Outdated Buildings

Amplified by the ongoing urbanisation and the ageing population, it was not until the 1990s that politicians grasped the size of the problem. The healthcare system was not fit for purpose. Something had to be done.

Over the years, Danish healthcare developed into a highly complex system involving multiple societal levels. Some hospitals were under jurisdictions of the local municipality, some fell under the county and others under the state, all intertwined in a complex web of interests and governing practices. The hospital buildings were, on average, 50 years old and not compatible with the new emerging healthcare practices focusing on treatment rather than hospitalisation. As Bent Hansen formulate:

> We had to do away with the building mass built for people hospitalised for weeks and the traditional measure of the size of a hospital on the number of beds. We had to change our understanding of a hospital, instead measuring the availability of professional qualifications (what kind of help can you get?) and how the specializations support each other. Because people who are really sick usually have multiple diagnoses.

The technological advanced and more individualised treatments connected to the specialisation required a greater population affiliated with each hospital to ensure volume for continuous improvement. Centralisation was thus a prerequisite for the specialisation, which was impossible in the outdated and decentralised infrastructure of the hospitals. The cardiologists at the large hospitals initially pushed for centralisation given their success in treating acute strokes, which could not be cured at the nearest hospital. Thus, the new healthcare system should include centralising treatments using the latest technologies, decentralised care, and speedy, professional emergency response.

Solution: Centralisation and Specialisation by the Construction of Super Hospitals

After 10 years of political negotiations, the structural reform of 2007 created a new regional setup, with 14 counties closed and 5 regions created. As a result, the division of tasks in the public sector was redistributed among the state, 5 regions, and 98 municipalities – a prevailing setup. The primary responsibility of the regions is to manage the healthcare system and run the public hospitals. The governing body of the regions is the regional council with 41 members, elected for a 4-year term and headed by chairpersons elected by their members. Representing the left political party "Socialdemokratiet," Bent Hansen was chairperson of the Danish region Midt – the front-runner region in the transformation. This made him the obvious candidate to chair the interest organisation of all the regions "Danske Regioner," which he was appointed to in 2007 and headed until 2017.

Parallel to the structural reform healthcare professionals, county officials aided by client advisors from the construction industry started to estimate the necessary investment. Acknowledging the limited experiences with hospital construction, they collected inspiration from leading healthcare providers in the other Scandinavian countries and the USA. The initial rough estimates by the regions identified a required investment of approximately € 14 billion, also considering the profound uncertainty. Venstre, the most influential liberal party, announced before the election in 2007 their ambition to spend €11–12 billion to modernise the dilapidated hospitals, of which €7–8 billion would be used for the construction of new hospitals, leaving a substantial residual for investments in new equipment. After Venstre won the election, the prime minister appointed a committee to develop centralised requirements, review the plans, and facilitate coordination between the different projects and regions. In this process, the €11–12 billion was reduced to €8 billion and later even to €5.6 billion still reserving a substantial for investments in new equipment (Juhl 2010).

The committee's central role was to review the design of a new physical layout of the healthcare system based on inputs from the regions' plans. The assessment of the hospital plans specifically emphasised (Juhl 2010):

1. Collection of functions and specialisations on fewer units (centralisation)
2. Compliance with the National Board of Health's recommendations in the emergency area
3. The prehospital intervention (GP and specialists)
4. Coherence with other regions

This included decisions on the number of hospitals, their relative placement, and the provision of specific healthcare services. This required a balance between centralisation (specialisation) and decentralisation in traditional care and simple treatments. As Bent Hansen formulates the region's challenge: *"You must understand what kind of patient population you have, what are specializations that need to be close to each other, so it provides the right setup for the patients?"*

Not only did the distance govern the overall design to the closest emergency. It also included evaluating the population in the catchment area varying from 41.000 on the small islands to 496.000 in the big cities. Furthermore, the new super hospitals should be well connected to recruit high-qualified employees usually living in the cities. Finally, the existing infrastructure was also considered, and decisions made about which hospitals had to be built, refurbished, or closed. The programme included 5 green field projects, 11 extensions (brownfield projects), and more than 20 smaller auxiliary funded projects (Bekdik and Thuesen 2016 and Godtsygehusbyggeri 2019). The new infrastructure over five regions is illustrated in Fig. 5.

The transformation of the healthcare system required a delicate balance between stability and flexibility. The physical locations of the hospitals are cast in concrete and thereby unchangeable. Still, the hospitals' design is flexible to facilitate the development and implementation of ever-changing healthcare practices. The patient rooms and operation theatres are thus not just designed for specific patients and treatments but more generic. Therefore, an operation theatre can both be used for hip replacement and cancer surgery. This creates better utilisation of resources between departments and adaption to future changes in practices and thereby support the government's strategy for state-of-the-art and cost-effective healthcare services. However, it is essential to remember that the buildings don't provide healthcare; people do.

While the buildings create the physical infrastructure, the doctors and nurses provide the healthcare. Thus, the facilities must create a context in which healthcare development can thrive. As Bent Hansen puts it: *"We must not take away people's*

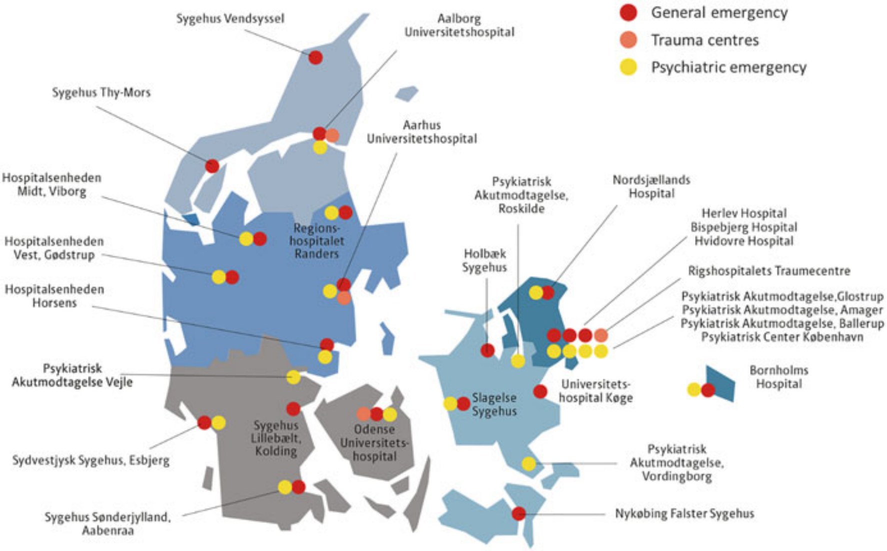

Fig. 5 Organisation of the Danish healthcare system. (Illustration by Ulla Hilden Danske Regioner, used with permission)

pride in working with healthcare. It is the employee's passion that drives the further development of healthcare."

To create ownership of the developed hospitals and prototyped new practices, several user-driven design processes were initiated locally in the different regions (Andersen 2016). One of the examples was "Innovationsstalden" (the innovation stable) located on a "green field" of one of the new hospitals. From 2012 to 2016, patients and professionals like doctors, nurses, engineers, and architects meet here for workshops and seminars to prototype and evaluate the practical layout, new equipment, and new processes of the hospital.

However, not all employees supported the new design and practices. The bigger organisational units at the hospitals resulted in fewer managers. Especially senior doctors holding managerial positions in some of the smaller hospitals were vocal. As Bent Hansen stated, *"Their position as an important person in the midsized city was challenged. They were moved to one of the bigger centres where they no longer held a superior privileged position. Some of my friends became enemies in this process."* Their resistance was substantially forming the public perception because *"who does the citizen trust the most: the doctor or the politician?"* (Hansen 2019).

Changing the healthcare system eventually affects all citizens as patients, relatives, and employees. A critical process has thus been to manage the public perception around the transformation. Being the overall head of the programme, Bent Hansen was one of the most frequent faces in the national and local press. In addition, he attended numerous public hearings all around the country, presenting, justifying decisions made and listening to the citizens' concerns. He exemplified this in the following story:

> "After the reform, Ringkøbing (a medium-sized town) became a part of the central Jutland region (Region Midt). The first thing we did was to shut down the emergency function of their hospital. There I stood in a public hearing facing several hundred furious citizens. Everyone attended. Late in the evening, there was an angry older woman in her mid-70s who got up and told her story. 'She was a heart patient and had been hospitalised so and so many times.' I had become a bit irritable. I knew what they meant, but that didn't change the decision. I asked her, 'If you now have a major heart attack again, where would you like to be hospitalised?' Then she said, 'I want to go to Skejby (the super-hospital 200 km away). I know the skilled professors there. They are the ones who can help me. But when they have treated me. Then I will go home and recover in my little hospital.' Her statement completely changed the vibes at the meeting because it was 'one of them' who articulated what it meant to be sick today." (Hansen 2019)

This story portrays a core feature of the healthcare transformation, creating acceptance of the new system by public engagement. While celebrating the inauguration of new hospitals is positive, the closing of hospitals is not (as illustrated in Fig. 6). Eventually, the programme also meant closing 12 hospitals – it was a prerequisite for getting the funding for constructing the new hospitals. Despite being the most challenging part of the programme, it is vital for the success of the transformation. Bent Hansen explained how he handled this.

> Shutting down hospitals was a bloody process. It has cost politicians their re-election. I started my political career in a small town called Kjellerup and was elected to protect the small hospital. However, it had to close. Then the locals asked me to take down the sign. And so I did. (Hansen 2019)

One might think that the intervention would be accomplished when the completed projects were handed over from the different project teams to the regions involved. But this was just when the real problems started to mature – especially in the green field projects. How do you move functions (including several thousand employees and equipment) from one hospital to another while still maintaining the fundamental services to the citizens? Extensive planning resulted in (expensive)

Fig. 6 Bent Hansen, together with the prime minister opening the new hospital Skejby (left) and closing the old Kjellerup (right). (Pictures: Tonny Fogmar, copyright Aarhus Universitetshospital (left) and Marianne Brink, copyright jysk fynske medier (right))

parallel services and a gradual transfer of functions. However, nobody had tried this before, resulting in way too optimistic budgets (only 20% of what was needed) and challenging organisational change processes. The new processes prototyped through the user-involvement processes happened to be challenging to implement when they suddenly included actual patients in new environments. Furthermore, the merger of different organisational units resulted in clashes of cultures and power struggles, potentially putting employees under severe pressure. Despite the substantial challenges, Bent Hansen believes the issues only are temporary given the exemplary leadership.

> There are huge challenges in getting the transformation going, but where the departments have worked two years in the new building – it works well. Then it is easier to keep areas sterile, isolating the particularly sick patients and giving them a far better experience. Create space for the patients and relatives, allowing them to stay together during the night. The better physical environment for the staff and the necessary technical equipment. Once these elements are incorporated, the benefits start to materialise. (Hansen 2019)

Implications: Increased Treatments and Ongoing Technological Development

We are currently at the end of this massive transformational programme of the Danish healthcare system. Until now, the programme has lasted over 20 years but will take another 5 years to complete. Despite the long lifecycle, partly implemented practices and challenges, the system successfully delivers high quality and cost-effective healthcare. A review of data illustrated in Fig. 7 suggests that the Danish healthcare system has been able to provide a high-quality service to citizens while fundamentally changing the system's logic – increasing effectiveness (treatments) while minimising the consumption of resources (e.g. bed days).

However, the transformation doesn't stop here. Setting up a system for success requires the ability to navigate the political landscape for making decisions, which in the short term satisfies the majority of the citizens while being open to future structural changes. Thus Bent Hansen envisions further closing of hospitals as the new hospitals is completed and connected to the evolving transport infrastructure. However, he is also concerned about the future.

> We know that technological development accelerates. Thus, we know change will happen, but we don't know if the buildings we have created are flexible so that they can be adapted to the needs in the future, supporting the professional development and thus continue to generate benefits. (Hansen 2019)

What could possibly happen? Closing of regions (already in the discourse), technologies are removing the need for centralisation (already happening within the heart area) or even challenging the requirements for hospitals altogether

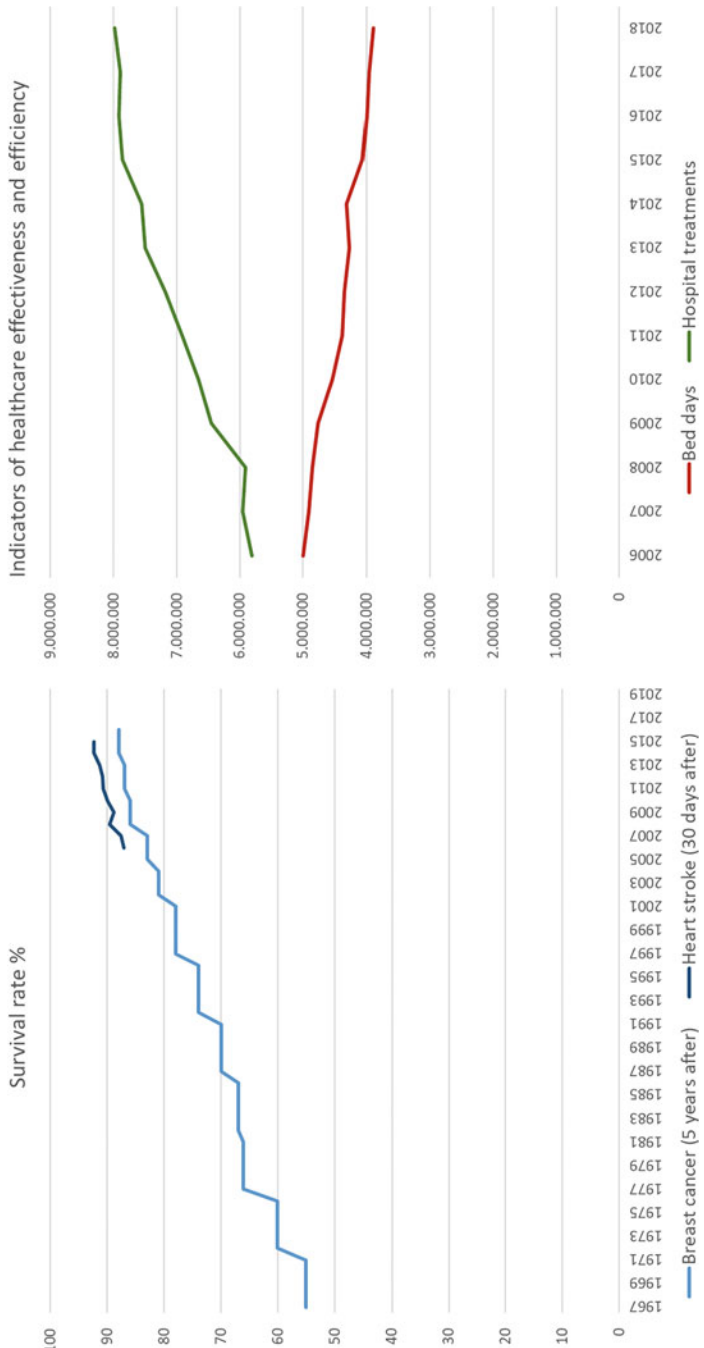

Fig. 7 Development of healthcare in Denmark (e.g. DST 2019)

Fig. 8 One example of the final hospital in Aarhus from 2021. (Picture: jwluftfoto.dk, used with permission)

through the revolution in personalised medicine, sensors, big data, and artificial intelligence. Or a global pandemic is testing the effectiveness and efficiency of the system (Fig. 8).

Reflections and Conclusions

This case has presented an intervention implementing super hospitals in Denmark to transform the healthcare system from hospitalisation to treatment. Besides offering a story of the development of healthcare, it provides unique insights into the design of engineering systems.

Engineering systems need to be seen in an international context. The development suggests that (global) trends and practices heavily influence the configuration of the healthcare engineering system. This is not surprising for several reasons. One is the apparent research-based treatment practices developed by doctors exchanging findings and best practices at international conferences and in international journals. This creates a shared body of knowledge, which guides the design and development of healthcare systems. It further constitutes the basis for cross-national bodies like the EU and OECD to establish measures for monitoring the development of the systems like the number of beds and CT scanners per 100.000 inhabitants. These measures explicitly identify performance indicators for evaluating the success of the healthcare engineering system.

Technologies maintain and transform engineering systems. The physical infrastructure in actual buildings constitutes both a conserving and disruptive factor in transforming the healthcare system. On the one hand, the existing hospitals enforce certain inefficient practices. On the other hand, the new hospitals' design and their relative placement create a structure that makes the continuation of existing (ineffective) practices difficult and stimulates the development of new practices. In this way, technology serves a dual purpose both as enabler and disabler guiding practices towards particular ends. Given the long lifecycle of engineering systems, it is essential to consider the (in)flexibility of technologies both from a technical perspective and in a temporal one.

The complex stakeholder landscapes in engineering systems require deliberate engagement strategies. The healthcare system will not fulfil its societal purpose without coordinated activities of professionals and users. Stakeholders' vested interests create an ambiguous environment of political agendas that might be incommensurable, like the physical placement of a hospital. Thus, handling stakeholders is not just a matter of satisfying individual users' needs but also shaping users' needs. This suggests that the communication around the engineering system is more important than the actual design of it. It further introduces user engagement as a central design practice. It is vital to reserve substantial resources for change management as it is hard to ensure smooth transitions from prototyped practices to scaled-up practices in real-life situations in the system.

Designing engineering systems requires a holistic perspective. The different stakeholders introduce different perspectives on the development of the engineering system. A nurse at a hospital will have a different view than that of a politician. To understand the (dis)functions of the healthcare system, it is essential to apply a holistic perspective that integrates various stakeholders' viewpoints. Bent Hansen's background as a historian combined with his insight into the political landscape created a unique profile for managing the transformation of the healthcare system.

System interventions require continuous collaboration and alignment of interests. The long lifecycles of physical infrastructures like hospitals add uncertainty. Interventions planned now might first materialise in 10 years – where the needs, possibilities, and capabilities inevitably have changed. The focus on realising long-term benefits might furthermore eventually require an ability to make and maintain tough decisions. This enforces policymaking that is governed by insights and consistency over a long period. This form of cooperative government is a key feature of the Danish society, as exemplified by the collaboration between the right and left parts of the political spectrum in transforming the healthcare system.

Acknowledgements

The description of the case is based on a conversation interview between Christian Thuesen and Bent Hansen. His time, insights, and shared opinion on the healthcare systems' past, present, and future are highly appreciated.

Case 2: Developing Deep Emergency Response Using AI

A Case of Copenhagen Emergency Medical Services Inspiring National and Global Actors

See Fig. 9.

Introduction to the Emergency Response System

This case example, "Deep Emergency Response: A case from the Copenhagen Emergency Medical Services," focuses on prehospital emergency care services and in particular explores the system innovation through technology intervention using artificial intelligence (AI) to support dispatch, pioneered at the Copenhagen Emergency Medical Services in the Capital Region of Denmark – one of the five regions in the country. Artificial intelligence in health and care services has been heralded both as a saviour and as a risk. It brings fundamental questions to the fore about what it means to be human and to be alive. Our guide in this case example is Freddy Lippert, CEO of Copenhagen's Emergency Medical Services, medical doctor, and associate professor at the University of Copenhagen. We interviewed Freddy Lippert in August 2019, and his words will guide us through the case in this part of the chapter. We begin by situating emergency care, the role of people and technology, and thinking in systems as a lead up to the example of AI use.

The Importance of Emergency Care

Increasingly, the global health community recognises the critical role that emergency care plays in delivering health services (Burkholder et al. 2019). While primary

Fig. 9 Copenhagen Emergency Medical Dispatch Centre with artificial intelligence "box" encased in a designed lampshade (Blomberg 2018; Blomberg et al. 2019). (Picture used with permission from CEMS)

prevention efforts are essential to reduce the burden of acute diseases, emergencies continue to occur in both the most developed and least developed countries. Emergency care is a health service that cross-cuts traditional disease-focused disciplines and provides prompt interventions for many disease-specific emergencies, including pregnancy-related complications, communicable and noncommunicable diseases, and injuries. Health systems in many countries are often fragmented and comprised of programmes with a narrow focus on disease-specific care. However, well-organised emergency care appropriately distributed across a country allows for timely coordination of services and resources and optimum efficiency and efficacy in treating a range of acute conditions, from out-of-hospital care at the scene of an injury or illness to treatment and stabilisation in the emergency unit, and early operative and intensive care (WHO 2019). Indeed, emergency care systems address at least 12 of the targets of the sustainable development goals (SDGs; targets 3.1–3.9, 3d, 11.5, and 16.1) and are particularly relevant to universal health coverage (Reynolds et al. 2017). Its importance is even more graspable, especially when barriers to healthcare access exist. People may seek care only when acutely ill or injured, making emergency care an essential component of universal health coverage – and for many people around the world, the primary point of access to the health system (Reynolds et al. 2017). Many proven health interventions are highly time-dependent – they save lives, but only when delivered in time. By ensuring early recognition of acute conditions and timely access to needed care, organised emergency care systems save lives and amplify the impact of many other parts of the health system (WHO 2019).

Technology in Healthcare and Emergency Care

Living in the Fourth Industrial Age revolves around artificial intelligence (AI), robotics, and big data, with great potential to help but also with risks to harm. Heralding a profound revolution, not least in medicine and highlighting, in particular, the magnitude of change in the way we live and work and perhaps in the way we think of ourselves and about what makes us human, Topol speaks of Dr Algorithm – AI in general and deep learning, in particular, bringing tremendous precision to diagnosis and prognostication (Topol 2019). Arguing further, *"that this isn't to say they will replace humans: what those technologies will do is a recommendation, one that is perhaps more accurate than it has ever been, but it will take a savvy, caring, and attentive physician and healthcare team to tailor that recommendation to-and with-the individual seated before them"* (Topol 2019). AI in medicine is not just a futuristic premise. The power of AI is already being harnessed to help save lives (Topol 2019, p. 4).

It Takes a System to Save a Life

Visiting Freddy Lippert, CEO of the Copenhagen Emergency Medical Services (CEMS) and medical doctor, and his team, we ask what the challenges are working for good health and well-being, with one of the targets being emergency preparedness? Lippert begins by saying, *"it takes a system to save a life, and our community and citizens are part of the system."* From citizens to community responders of the emergency services, they all provide vital links in the patient's chain of survival when suffering from cardiac arrest (North East Ambulance Service and Ciphermed 2017). One in six will have a stroke in their lives. Acting fast and cooperating in the process is core – from feeling the symptoms, to placing a call, to the call taker/ dispatcher suspecting a stroke, to sending an ambulance to paramedics arriving, to calling into an emergency department at a hospital. In other words, Lippert continues, *"it takes people, institutions, and technology to cooperate to provide the best possible care for the patients. How the parts are linked, their interdependence, determines the performance of the system,"* in this case, prehospital medicine and as such directly impacts life. *"I worked from individual patients now to system care and try to organise it in a different way because I think that it saves more lives actually and provides better care if you do so,"* says Lippert.

Building on the stated importance of thinking in systems, emphasising the links in the chain of survival and in a changing world, we ask how to prepare and train the next generation in the directions of the future when the world is changing faster than ever? Freddy Lippert emphasises that *"we cannot predict, we don't know what will happen in the future. What we can do is proactively create the future"* (Impressions from EMS2018|EMS2022 Scotland 2018). And that he does by pioneering multiple initiatives for emergency care system innovation.

Linking to ensuring the best possible human care or people-centred care delivery (WHO 2019), Freddy Lippert emphasises *"we ongoingly ask ourselves what interventions are needed for health innovation and what interventions are taken, and, given that people make the world … we ask ourselves how might we best use technology for people? How might we best think in systems to save lives?"* (Fig. 10).

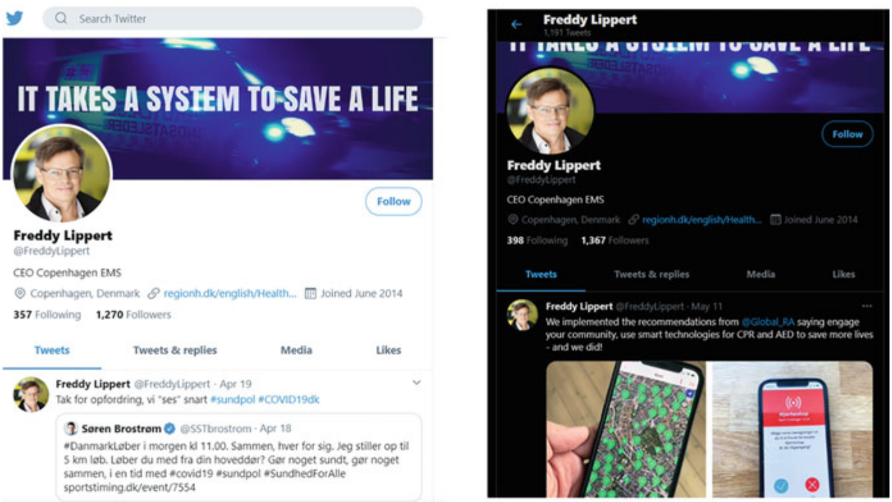

Fig. 10 Freddy Lippert, CEO of Emergency Medical Services Copenhagen and MD. Screenshot of his Twitter feed on 26 April 2020. (Lippert 2020) and 15 May 2021. (Lippert 2021). (Picture used with permission from CEMS)

Situation: Handling 130.000 Emergency Calls Per Year

Freddy Lippert, CEO of the Copenhagen Emergency Medical Services (CEMS) and medical doctor, heads up a pioneering programme at CEMS. Continuously pushing the innovation frontiers of emergency medical care services, he and his team recently began introducing AI for emergency calls. Using AI within dispatch at Copenhagen Emergency Medical Services (CEMS) is to be seen in the context of many system innovation initiatives at CEMS. Also, prehospital healthcare, or emergency medical services, varies significantly across the globe, also within Western countries, and is continuously developing (Lindskou et al. 2019). How does it look in Denmark?

Emergency Medical Services (EMS) in the Capital Region of Denmark

In Denmark, emergency medical services are coordinated by the five regions countrywide, and all emergency medical services are free to Denmark's citizens as part of its public healthcare system (Healthcare Denmark 2019; Lindskou et al. 2019).

The Copenhagen Emergency Medical Services (Region Hovedstadens Akutberedskab/EMS in the Capital Region of Denmark) provide immediate emergency care for people with acute illness or injury in the region and reach about one-third of Denmark's population. Copenhagen EMS also runs physician-staffed critical care units/emergency cars, interfacility acute and nonacute transfers, a prehospital psychiatric critical care unit, and an ambulance that addresses social issues (*sociolance*).

The 1-1-2 emergency number connects to the Emergency Medical Dispatch Centre which handles about 130.000 medical emergency calls annually (Blomberg et al. 2021). In the Copenhagen EMS, calls are responded to by health professional examining officers that are mainly paramedics (30%) and nurses (70%) (Danish Ministry of Health 2017; The Capital Region of Denmark 2020c).

The Emergency Medical Dispatch Centre of the Capital Region of Denmark is the coordinating unit for all prehospital services with ambulances, emergency physician cars, and general transport for the sick. The region's Emergency Medical Dispatch Centre receives calls for all ambulance services, emergency physician, and ambulance transport, and requests for assistance from the national Helicopter Emergency Medical Services (HEMS). Nationally, four helicopters provide helicopter emergency medical services (HEMS), and these can be dispatched by any of the five EMS organisations in Denmark (Gates 2019).

The Emergency Medical Dispatch Centre has a manager for the emergency operations centre, an operative manager and a health-professional manager. Technical sub-managers and health professional examining officers are also employed at the centre. The technical sub-managers receive requests for assistance and ensure that the best possible solution is available. Their assessment involves needs and degree of urgency, taking into account resources and logistics. There are, on average, about 700 responses every day, of which about 60% are emergency tasks. Health professional examining officers receive emergency calls from 1-1-2 to 1-8-1-3 numbers. In case of 1-1-2 calls, the health professional staff will send the proper help if needed. Staff will subsequently assist the caller on what can be done until help arrives. The medical helpline 1-8-1-3 has also been set up at the Emergency Medical Dispatch Centre and offers citizens counselling in the case of acute illness and injuries as well as information on waiting times at the acute admissions centres of the region (Healthcare Denmark 2019, p. 22). Today the medical helpline triage all patients to the different emergency department, including booking a specific time.

Breakout Box: Key Figures of the Copenhagen Emergency Medical Services (CEMS)

Copenhagen Emergency Medical Services (Copenhagen EMS) is an independent public health organisation established in 2011. It is part of the Capital Region in Denmark and part of Greater Copenhagen. Copenhagen EMS provides emergency care for a population of 1,8 million people, approximately one-third of the Danish population.

Ambulances, emergency response units: The region's ambulance service comprises 47 emergency response units, distributed as follows (The Capital Region of Denmark 2020b):

- Twenty-five ambulances with full 24-h activity.
- Thirteen are 24-h ambulances with an expected low activity.
- Nine are 24-h ambulances with either day or evening activity for a 12-h period.
- There are an additional 13 reserve ambulances for use when others are out of service or when there is an exceptional demand.

Crews:

- Twelve of the ambulances are crewed by one paramedic and an ambulance assistant.
- The remaining ambulances are crewed by one emergency medical technician and an ambulance assistant.

Calls and missions in Copenhagen Emergency Medical Services:

- The Emergency Medical Dispatch Centre handles 350.000 ambulance missions per year.
- Of these, there are 130.000 emergency ambulance missions on European emergency number 1-1-2 per year.
- The medical helpline number 1-8-1-3 handles about 1,2 million calls per year.
- Other "jobs" such as transportation of sick, approximately 600.000 missions a year.

History of System Innovations at Copenhagen Emergency Medical Services

Emergency medical services play an essential role in meeting global healthcare challenges, and Denmark has fostered several new initiatives to improve future emergency care. Looking at the evolving structure and processes of Copenhagen EMS, *"much of the developments and progress especially focusing on system care to achieve effective primary care with the patient at the centre that we see now began in 2008,"* says Lippert, *"when the National Board of Health commissioned a 10-year plan to improve health services throughout Denmark."* As part of that plan, EMS Copenhagen CEO Freddy Lippert was instrumental in improving patient care (Gates 2019).

CEMS is constantly exploring new ways to improve emergency care – in close collaboration with hospitals, municipalities, private companies, individual patients, their families, and the community/society (Healthcare Denmark 2019, p. 3). Currently, using artificial intelligence (AI) in dispatch to recognise out-of-hospital cardiac arrest during emergency calls is being conducted in a retrospective trial and prospective trial. Studies have been published, and a PhD thesis defended at the University of Copenhagen. Lippert also points to ambitions for using AI in ambulances on-site and a programme for video-aided telephone CPR in its starting phase. Now, when writing this, being in the midst of the COVID-19 crisis, we see chatbots implemented with sweeping uptake for answering people's immediate queries and concerns.

Recounting the historical development, Lippert speaks of many interventions as examples of prehospital innovations improving survival and in close connection with colleagues internationally and, particularly, as a strong driver in the European emergency medical services (EMS) leadership network mentioned earlier. This includes the transition from police to EMS as main call takers of 1-1-2 when a medical emergency is called for, the out of office hours community medical helpline 1-8-1-3, or heart runners and other citizen community education for providing on-site CPR.

2011: Transferring 1-1-2 emergency medical calls from police to EMS: Prior to this plan, the police department was the sole call-takers of 1-1-2 calls. As of 2011, all emergency and nonemergency calls are handled by one emergency medical dispatch centre. The Danish emergency number, 1-1-2, covers all emergencies – accidents and emergency medical situations, fire, or serious crime – and is solely intended for emergencies requiring urgent assistance (Life in Denmark 2021).

2014: Focus on primary care 1-8-1-3 number: An innovation that was first initiated in the Capital Region of Denmark in 2014, 24 h a day, 7 days a week, and will now be rolled out nationwide is the establishing a medical helpline nonemergency number, 1-8-1-3 which the emergency medical dispatch centre answers in Copenhagen. The call-takers are nurses and physicians working in the same call centre as the 1-1-2 call-takers and dispatchers. Citizens in Copenhagen are well-versed in using this medical helpline that is also open outside the opening hours of family doctors (GPs). Copenhagen EMS has seen its popularity growing every year, with a million calls received annually (Lippert 2019). Citizens calling

1-8-1-3 are helped to secure an Emergency Department (ED) timeslot where they will be seen, using EMS Copenhagen's ability to view current ED capacity. The appointment is sent via text message to the patient. Copenhagen's public safety answering point (PSAP) collaborative nature also allows for call transfers: 1-8-1-3 callers who need an ambulance are transferred with a click of a button, and 1-1-2 callers can also easily be transferred to 1-8-1-3 nurses. This has placed EMS in Denmark and its call centres in a central position, integral to the focus on primary care – which is by far not the same as in many other developed nations.

2016: Rate your degree of worry: In addition to organisational and structural innovation as the above examples, Copenhagen Emergency Medical Services initiated a research study to incorporate the caller's perspective. Freddy Lippert tells us that *"[. . .] we also had a project where we actually asked people how they would rate their worry. Not your disease or the risk. But your worry. What is your worry? The idea for instance about the degree of worry, was that we thought that people would actually know they are more sick than we believe? So when you have a conversation with one of the nurses or physicians, they might talk you down, don't worry, I have heard of this a lot of times; it is not serious and things like that. But the caller is still worried, and so we thought that maybe we could have a look at the data. And we looked at are they going to be admitted to the emergency department, are they going to call again, are they going to be hospitalised, are they going to an operation, are they going to have x-ray interventions and things like that. And that was completely correlated to what happened afterwards. So you can really trust your own gut feeling on your own disease. There are few exceptions and few people who miss that but in general, and the big data we have actually proves that, you can trust that. And that is, I think, going to be a game-changer in healthcare."*

Using behavioural theory as base for the "patient-centred" intervention, the citizens'/callers' perception of urgency, defined as the degree of worry, in acute care telephone triage was studied. It was hypothesised that the caller's perception of urgency of the problem can potentially improve decision-making in telephone triage. Questioning the caller's perspective invites the caller to take part in decision-making and facilitates information sharing. Moreover, there is a possibility that the cognitive task of rating a degree of worry could provide an opportunity to empower callers by teaching patients health behaviour, such as advising on self-care (Gamst-Jensen et al. 2018).

2019: Heartrunners and AEDs: Citizens as a lifesaving resource: Another initiative to train citizens in CPR has increased the rate of bystander CPR to more than 70%, up from around 20% 15 years ago. In the first year of using the Heartrunner, approximately 25.000 citizens registered to volunteer, and 6.500 have been involved in over 800 resuscitation attempts. In addition, Copenhagen EMS keeps automated external defibrillator (AED) locations continually updated on a real-time map call-takers can use to direct helpers to the nearest device. As of September 2019, approximately 20.000 AEDs have been registered across the nation (Gates 2019). Following the cardiac arrest suffered by Denmark midfielder Christian Eriksen during a Euro 2020 match has seen a sevenfold increase sign-ups, people volunteering to be trained as "heartrunners."

Complication: Opportunity for Improving Response Time and Detection to Save Lives

On the one hand, we have an opportunity, a burning desire, to continuously innovate to save more lives, and, on the other hand, we have a burning platform to save lives, says Lippert. Copenhagen EMS prides itself on being a frontrunner in research-based and data-driven system innovation.

One challenge they face – and health systems worldwide – is getting even better at response time and accurate detection of out-of-hospital cardiac arrests (OHCA). The Emergency Medical Dispatch Centre in Copenhagen receives about 130.000 emergency calls per year, of which 1–2% are OHCAs. It is not always easy to understand what callers are telling the dispatcher. And if the dispatcher does not recognise a cardiac arrest, *"we don't provide dispatcher-assisted CPR, and we don't refer callers to automated external defibrillators (AED),"* says Lippert.

The dispatch centre identified 75% of OHCA, *"meaning that they [the call takers] miss about 25% [...] Even though they are medical persons. In other countries, they are usually non-medical persons just following a protocol. But here we have medical persons. They should be better than non-medical persons. But they are also biased, and it is a difficult task. Of course, they don't remember all the cases, they don't get the feedback, just like machine learning does, so it takes a long time to improve. Even though we have a lot of education and emphasis on cardiac arrest, it is not so easy."*

In other words, emergency medical dispatchers fail to identify approximately 25% of out-of-hospital cardiac arrest cases, thus losing the opportunity to provide the caller instructions in CPR. It is hard to gain experience and improve OHCA recognition for the individual call taker/dispatcher. As such, Lippert and his team initiated a research project on improving OHCA recognition and time to OHCA recognition. EMDC set out to investigate if artificial intelligence (AI) can help call-takers better identify cardiac arrests; whether AI can be used as a decision support tool in medical dispatch, as a tool to support, not as the final decision taker. The initial study using automatic speech recognition and cardiac arrest classification was done on audio recordings of all calls taken in 2014. In a recent trial, the AI successfully identified 90% of cardiac arrests over the phone (Blomberg et al. 2019).

Solution: Technology Intervention Using AI to Support Dispatch

The case is AI pattern recognition for detecting out-of-hospital cardiac arrest (OHCA). Lippert and his team examined whether a machine learning framework could recognise out-of-hospital cardiac arrest from audio files of calls to the emergency medical dispatch centre (Blomberg et al. 2019). The associated call was retrieved for all incidents responded to by Emergency Medical Dispatch Centre Copenhagen in 2014. The performance of the machine learning framework was compared to the actual recognition and time-to recognition of cardiac arrest by medical dispatchers (Blomberg et al. 2019). More than 100.000 emergency calls from the whole of 2014 were examined, of which 918 (0,8%) were out-of-hospital cardiac arrest calls eligible for analysis. Compared with medical dispatchers, the machine learning framework had a significantly higher sensitivity (72,5% vs. 84,1%, $p < 0{,}001$) with lower specificity (98,8% vs. 97,3%, $p < 0{,}001$). The machine learning framework had a lower positive predictive value than dispatchers (20,9% vs. 33,0%, $p < 0{,}001$). Time-to recognition was significantly shorter for the machine learning framework compared to the dispatchers (median 44 s vs. 54 s, $p < 0{,}001$).

The team concluded from this study that applying a machine learning framework on raw audio files of emergency calls to identify out-of-hospital cardiac arrest (OHCA) showed significantly higher sensitivity and similar specificity than what was recognised by professional medical dispatchers. Furthermore, the machine learning framework was significantly faster than medical dispatchers in identifying OHCA, albeit with a lower positive predictive value. Machine learning may also play an essential role as a decision support tool for emergency medical dispatchers in other time-critical conditions (Blomberg et al. 2019). Having said this, limitations include that the predictions by the machine learning framework are made at the termination of the audio recording. In a live setting, the end-of-call prediction is less valuable than a prediction made while the dispatcher is still on the phone with a bystander. The machine learning framework would need to alert the dispatchers in the case of a suspected OHCA when there is satisfactory confidence in the prediction before the end of the call.

The results from this study need to be tested in another emergency medical setting to prove transmissibility to other languages and organisational cultures. If an OHCA can be recognised from a short conversation over the phone, using machine learning to identify other time-critical incidents as stroke, acute myocardial infarct, or sepsis holds great potential. These conditions have serious health and economic impact and are in the USA over twice as prevalent as OHCAs. Ideally, the use of machine learning should be tested in a randomised controlled trial to measure its impact on patient survival and EMS system operations (Blomberg et al. 2019). In the Copenhagen EMS, a prospective randomised trial is currently underway with calls in real time. When the machine predicts a cardiac arrest, 50% of the alerts are shown to the dispatchers. The question that is now before us is, can AI work on live audio in clinical practice?

Implications: (Un)expected Benefits of AI Implementation

Lippert and his team achieved tripling the survival rate (GRA 2019). *"But we also feel a responsibility in what is the final outcome of these patients. So what we looked at is that if you were at work, went to work everyday, had a cardiac arrest, who, what proportion went back to work. 75%. [. . .] Yeah. And when we looked at the people thought that it would be 10% maybe. But it was actually 75%"* (Lippert 2019).

Going forward, now and in the wake of the COVID-19 crisis, we are experiencing, as some call it, a new normal. *"New challenges drive changes [. . .],"* writes

Freddy Lippert in his Twitter feed on April 8, 2020, *"[. . .] this is the start for using chatbots, artificial intelligence and videostreaming in EMS"* (Lippert 2020).

For the medical helpline 1-8-1-3, what happened is that Copenhagen EMS saw calls to its emergency lines almost double after the outbreak began, with around 2,000 calls coming in daily by early March from worried people who were showing symptoms of COVID-19 or had questions about the disease.

As the coronavirus pandemic began spreading across Europe in early 2020, the number of calls to Copenhagen Emergency Medical Services was surging fast. The organisation, which provides emergency care for about one-third of Denmark's population, saw calls to its emergency lines almost doubled after the outbreak began, with around 2.000 calls coming in daily by early March from worried people showing symptoms of COVID-19 or had questions about the disease. The organisation opened a second call centre to handle the inquiries, but that wasn't enough. "We realised that many people had the same general questions," says CEO and medical doctor Freddy Lippert. *"A virtual assistant seemed like a great option to decrease the load on the workforce. Not only can it handle much more volume than the call centre. It can run a symptom checker and identify high-risk patients according to medical protocols in the same way medical staff would, directing those in need to a 'warm handover' with a human."*

Having experience with AI application out-of-hospital cardiac arrest prepared CEMS for a fast response in broader use for queries from people calling the 1-8-1-3 number. CEMS created and launched its COVID-19 bot in mid-March in less than 2 days using the Microsoft Healthcare Bot service (Bach 2020) (Fig. 11). The bot answered 30.000 calls the first day, Lippert says, lowering the number of inquiries to Denmark's emergency number and reducing demand on healthcare workers. *"It was a great service for those who used the bot, and it allows us to focus on patients that really need help,"* Lippert says. *"We saw the immediate effect."* The bot was

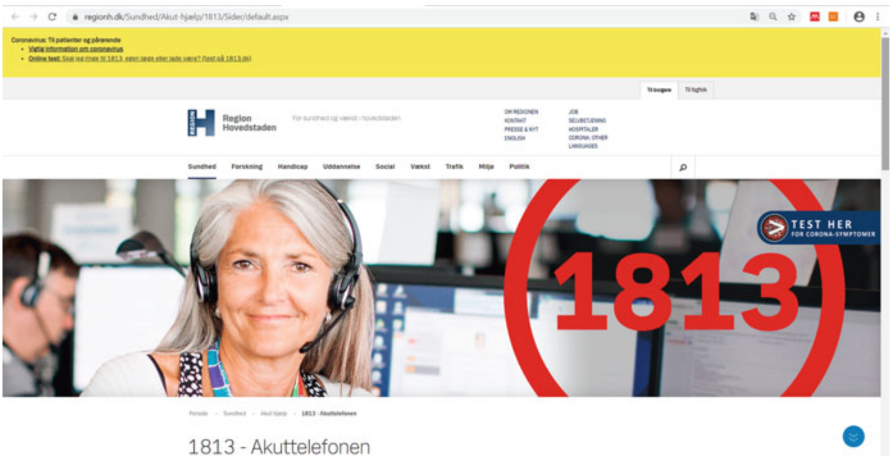

Fig. 11 Medical helpline 1-8-1-3 of the Copenhagen Medical Emergency Services. (Picture: 1813 – Akuttelefonen, used with permission from CEMS)

considered successful and was quickly rolled out nationwide. Stephanie Lose, president of the Danish Regions, says the tool will help relieve the burden on emergency lines throughout the country and ensure callers in most need of help can be assisted sooner. *"I am proud that at a critical time during the COVID-19 epidemic, we have succeeded in scaling a solution from one region to the whole country,"* she says (Stephanie Lose – Regionsrådsformand i Region Syddanmark (V) no date).

Reflections and Conclusions

The case in this part of the chapter has shown that thinking in systems plays a vital role in supporting advanced medical care, especially in emergency care, where time is essential to the quality of care the patients receive and their health outcomes. Reflecting on the past and current interventions Lippert help us to identify core elements of effective engineering systems design, navigating complex stakeholder landscape, creating data and research evidence, and engaging people. It is not just about technology. *"[. . .] I think we are not going to invent new technologies. Very difficult. Already out there. [. . .] The way we are doing it is how can we best implement new technology and you can say system design and system thinking to provide better patient care. And one thing which is in my opinion important is looking at what are the citizens actually doing themselves. And what do they want? And then we can try to change our service to them"* (Lippert 2019).

Complex stakeholder landscapes hold challenges and opportunities for collaboration and acceptance. When probing further into how Lippert and his team went about implementing, Freddy Lippert reflects on the complex stakeholder landscape, including the medical profession, policymakers, and patients or citizens and public community as a whole, people's reactions, and the importance of data- and science-backed-up evidence. *"For implementation of innovative measures such as AI in dispatch, there is a time delay in the feedback loops, e.g. convincing the decision-makers, convincing the wider public etc. [. . .] A major challenge we have in patient care is the traditional thinking of healthcare personnel. So, they don't rely on new technology, they think it is funny, they want to use it, but they don't rely on it. A lot of our colleagues don't think out of the box of what we can use from other areas in healthcare."* Exaggerating a little to illustrate the point, Lippert continues by saying, *"the system boundary within healthcare is that we traditionally work only within healthcare. We don't work with other areas because we know better. We don't work with private companies because we know better, we don't trust them, we don't even work with media because they tell lies and because they don't trust us, and we don't trust them. So, I think that is a major barrier, actually, meaning there is a lot of information in other parts of the society that we don't know of [. . .] So, I think that is the openness and working together outside your area of responsibility to get new ideas and do well, I think that is very important."* Lippert further refers to policymakers as another core stakeholder group. *"They [politicians] want to do the best for the patients, and as long as the community, as long as you can document* *what you are doing, they are willing to support you. But they should also trust that you are working in a responsible way so that you are not just always asking for money for something which doesn't benefit a lot"* (Lippert 2019).

Research evidence and data stimulates learning and innovation locally and globally. Lippert and his colleagues have published more than 50 research articles on EMS in multiple journals in the last few years alone. *"We feel the responsibility to use the data in a scientific way [...] I don't know many EMS organisations internationally that are doing research actually. Some in South Korea, some in Singapore. Some in a few US but it is all. It is not as integrated as it is here. I think that it is one of our benefits. But I wanted to be even more integrated with what is going on at DTU or private companies, or University of Copenhagen, so that we will work more closely and faster because the speed is important when you are talking about innovation and implementation"* (Lippert 2019).

> I believe that you can convince most people with data. [...] I can maybe give one example [...] the emergency call 112 has 50–60 years been taken by the police. So, they would take those calls and they would make an assessment based on a few algorithms, for instance, within healthcare, whether they should have an ambulance or not. And then, it was sent to the ambulance provider to go and see the patient. It has been like that for years. We have discussed that, and my argument was that we as healthcare region are paying for the ambulance services, we have the responsibility for the patients, why don't we take those calls and make an assessment. (Lippert 2019)

Instigating this major redesign started in this way nearly 15–16 years ago. *"We tried to argue and didn't get through, and then I was told; forget that, it is a great idea, but forget it, it is not going to happen, we have different authorities. Some of them are very strong, so we are not going to do that. So you have to forget that."*

Lippert and the team taking a long-term perspective would not take no for an answer. *"I realised that we needed to get some more data. This is the change we have to make to provide better care to the patient because this is the most important thing. And now, if you look internationally, people are so interested in dispatch. It used to be just a phone call where you sent an ambulance. Now, people know that this is the key to emergency patient care. You actually are in control of what is going on in such a command and control centre, and that you have resources and provide the right help. It is not an easy task, but it is a huge change"* (Lippert 2019).

Engaging the community is key to realising the benefits of the system and interventions. According to Lippert, it is important to reach out to citizens and the wider public. *"Because first of all, most people don't get in contact with us. They get in contact with us when things go wrong. I believe strongly in prevention, I believe strongly in engaging the community taking care of themselves and in the right way."* Copenhagen EMS is investing a lot in educating the public, the heartrunner initiative mentioned earlier is one example and information on contextualising information in health apps. Also, using social media: *"We thought that we need to build up a kind of experience and relation to the public through social media to get information out at the right time and some of it is just for information, some is to act on, some causes curiosity and people want to know more"* (Lippert 2019).

As a broader reflection beyond a particular intervention in how emergency medical services are organised, Lippert also refers to the position of emergency services into the wider healthcare system in Denmark and elsewhere. During the past few decades, especially, Emergency Medical Services (EMS) have played an increasingly important role in the Danish healthcare system – as other EMS organisations worldwide. It has transitioned from the traditional expectation and picture of mainly being in the business of deploying ambulances and reducing response time to designing system care, focusing on creating a data-driven and evidence-based solutions for innovating better life by integrating technologies to ensure appropriate early treatment and to facilitate the best possible collaboration and coordination between emergency wards, specialised hospital departments, municipalities, fire and rescue services, community volunteers, and local healthcare providers, patients, families, and society as a whole (Healthcare Denmark 2019, p. 22).

The Emergency Medical Services (EMS) is usually the initial, if not the only, point of contact for patients with acute illness and injuries. As such, the EMS is responsible for initiating care and operates as a gatekeeper for the entire healthcare system. *"Emergency Medical Services (EMS) has transformed over the last decade from patient transport to advanced medical care provided at scene and during transport to definitive care. Emergency medical dispatch is now the gatekeeper to emergency care in many EMS systems and the provider of telephone assisted lifesaving instructions from CPR to emergency childbirth. The dispatch role is more than identification, prioritizing and dispatching the right resources to the patient, now serving as an important clinical hub"* (EMS Leadership Network no date).

A systems perspective enables emphasising the sociotechnical intricacies of engineering systems. A clinical trial conducted by Copenhagen Emergency Medical Services and partners that we labelled "deep emergency" in this chapter is still ongoing at the time of print of this handbook. Where exactly AI goes for cardiac arrest dispatch support is yet to be seen. Freddy Lippert emphasises in closing that looking at technology alone will not work. Yet, looking at technology as a virtual assistant and using machine-assisted diagnosis to improve diagnostic accuracy is one link in the chain of survival that may help improve efficiency and health outcomes. The debate is undoubtedly lively in literature and media, and COVID-19 is also playing its part. *"David Marr, a British neuroscientist, famously said, trying to understand perception by understanding neurons it's like trying to understand a bird's flight by studying only its feathers. Just cannot be done," a*s quoted in Topol (2019, p. 227). Wrapping up the interview, I ask Freddy Lippert for a final summary thought. He smiles assuredly and says, *"we are proud to be among the leading Emergency Medical Services (EMS), innovative and taking a systems perspective for saving lives."*

Acknowledgements

The description of the case is based on a conversation interview between Anja Maier and Freddy Lippert in August 2019. His time, insights, and views on the present and

future of emergency medical services and expertise and passion for "it takes a system to save a live" are greatly appreciated.

Case 3: Decarbonising Global Shipping in a Global System Transformation

A Case of the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
See Fig. 12.

Situation: The Need for Zero-Carbon Shipping

Much of our current economic model – and subsequently our industrial activity, jobs, and social welfare – is based on the idea of global trade. Trade enables each country to do what they do best. Without trade, it would be difficult to imagine how the "knowledge economy" of Europe could exist or how we could support high-paying, specialised engineering jobs and global company champions that depend on worldwide sales.

This global trade is underpinned by shipping. More than 80% of the global trade (by volume) is carried on the approximately 70.000 merchant ships consuming 300 million tons of fuel (Stone and Li 2021).

Global shipping is the key enabler behind globalised trade, emitting 940 million metric tons of CO_2 annually (Tiseo 2021), while other vessels contribute another 140 million tons. Shipping alone accounts for around 3% of the global CO_2 emissions. Given the development of global trade, these emissions are expected to increase between 50% and 250% until 2050 in a business-as-usual scenario.

Fig. 12 The Mærsk Mc-Kinney Møller, one of the largest container ships in the world. It carries over 18.000 20-foot containers with a crew of 13. (Picture credit: Slawos 2013 – CC BY-SA 3.0)

In 2020, the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping was established in Copenhagen as a not-for-profit institution to decarbonise the maritime industry (Center for Zero Carbon Shipping 2021).

Breakout Box: Key Figures of the Global Maritime Shipping Industry

- Global maritime shipping accounts for over 80% of global trade – over 11 billion tons of goods, or 1.500 kg per person per year.
- There are over 70.000 merchants ships active globally.
- Fuel consumption is 300 million tons annually, the majority of which is diesel and heavy bunker fuel.
- Maritime shipping is considered a "hard to abate" sector regarding greenhouse gas emissions.

Complication: The Challenges of Net Zero in a "Hard to Abate" Industry

The shipping industry is labelled as a "hard to abate" sector concerning CO_2 emissions, and the investments needed for decarbonisation are estimated trillions of USD until 2050. However, to make meaningful contributions to the fight against climate change, significant emission reduction efforts have to be achieved by 2030 already. Given the long life cycles of the shipping industry investments, substantial changes have to be implemented right away during this decade (Balcombe et al. 2019).

Due to the complexity of the sector and the difficulty to abate emissions, maritime shipping was not addressed in the Paris climate accords. The International Maritime Organization (IMO) was asked to facilitate decarbonisation efforts, and in 2018 announced the goal of reducing emissions by 50% until 2050. While a step in the right direction, the goals of the Zero Carbon Shipping Center are more ambitious.

A key challenge is the complexity of the maritime stakeholder landscape. The value chain in itself is complex, with ship designers, shipyards, owners, operators, customers, port operators, and all the associated commercial functions, but also their genuinely global distribution, operating in hundreds of different legal and regulatory environments. As the purpose of ships is to trade, changes cannot be implemented locally, as ships travel – by their design and purpose – between locations. Also, it is a very diverse industry, comprising relatively short-range shipping vessels and blue ocean container ships, bulk carriers, and tankers. A coordinated, global transformation effort has never been attempted.

While 2050 may sound like a distant goal, the Center has started to develop concrete actions that need to be taken now to achieve ambitious future targets. For example, large vessels have a minimum life span of 20–30 years, with construction lead times. So the vessels of the 2050 fleet will be entering service in 2030, or at the very least must be orderable at that point. That requires a massive effort to make low-carbon or zero-carbon propulsions options viable and attractive for investors, not by 2050 but by 2030. As a co-lead of the international public-private partnership Mission Innovation (Mission Innovate 2021) and a Knowledge Partner in the Getting to Zero Coalition of the Global Maritime Forum (2021), the Center supports the Mission goal of having at least 200 deep-sea vessels deployed at that point in time, bringing global deep-sea fleet consumption of zero-carbon fuels to at least 5%, showcasing decarbonised technologies.

The Center pursues both a "top-down" as well as a "bottom-up" strategy to identify, prioritise, and engage in activities that further its goal of decarbonising global shipping operations.

The top-down perspective is a systemic perspective aiming to identify "critical elements," i.e. systemic interventions that will lead to a positive reinforcing effect to drive desirable system behaviour. It also aims at understanding the relationships and synergies between those factors. Factors are categorised into the fields of (1) critical technology capabilities, (2) critical regulatory needs, and (3) critical factors driving end-customer demand for zero-carbon shipping.

While the top-down approach relies on engaging senior executives across the commercial and public stakeholder landscape, the bottom-up approach relies on a quantitative model of the energy pathways in the shipping industry. It is a technical-economic model quantifying factors such as fuel production and transport, ship and port operations, and retrofitting activities. The Centre developed the model with the help of on-site co-located subject matter experts from their partners to model the entire energy pathways accurately. Fundamentally, the model allows quantifying the total cost of ownership for operators and investors of alternate future technology and operating scenarios. This enables a bottom-up identification of critical capability gaps, cost factors, and risks that hinder investments towards zero-carbon shipping.

The scenario cost modelling is used to subsequently evaluate candidate projects and shape the programme content in three major areas: (1) Identify critical fuel technology risks and gaps that need to be closed to increase the attractiveness of investments; (2) Efficiency of supply chain, ship and fleet operations, within and across operators; and (3) Custom-design support for "first movers" by reducing, sharing and transferring investment risks.

One of the reasons the Center has made significant investments into this quantitative whole-system-model is that the shipping community will face hard economic choices moving forward. The Center expects that it can inform tough decisions by the most reliable data and quantitative assessment available in the industry.

Of particular importance is creating partner networks, or innovation ecosystems, at different levels of the value chain. The Center begins by cooperating with "big players" in the ecosystem that have the resources to support, for example, the secondments of personnel to the Center. There is active planning regarding the productive engagement of a broader base of global stakeholders. The value the Center aims to add to these innovation ecosystems revolves around the identification and coordination of joint value-adding activities and business opportunities, "match-making" of partners with similar interests and complementary capabilities, and the creation of positive publicity for emerging success stories.

Solution: The Sociotechnical Interventions Pioneered by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping

The Center's goal is to "infuse confidence to act in time" globally in public and private actors. This includes the support of wide-ranging technological innovation and their de-risking to a maturity stage where established market mechanisms lead to their adoption and diffusion. Part of that activity is to engage stakeholders in building an industry-wide transformation strategy that leverages technological, economic, and regulatory changes to create a carbon-neutral shipping industry. What makes the Center unique is that it is facilitating industry leadership in decarbonising this hard-to-abate sector.

Investors and Financial Institutions Will De-Facto Implement the Decarbonisation: De-risking Investments to Drive Transformation

The stakeholder landscape involved in decarbonising shipping is complex, but at the end of the day, also very simple: investors commission and buy vessels, and they choose the vessel and its carbon footprint. So, to deploy low carbon technologies, they must appeal to investors. That includes a favourable lifecycle cost (including the impact of global carbon pricing), but reliable technologies must also lead to resilient operations. This is crucial for the operators and the banks that provide the loans for investments and the insurance companies underwriting the ventures.

Facilitating Technology Development: From a System View to Component Requirements

Decarbonisation of shipping will be enabled by the next generation of ship designs, fuels, and fuel infrastructure. While some alternative fuels, such as LNG, are reasonably familiar today, others, such as green methanol, green ammonia, or green hydrogen, are not. None of them present unsurmountable problems from a physics or engineering point of view – their chemistry and engineering properties are fundamentally well understood. However, scaling technologies proven in the laboratory and small-scale application to annual global use on a terawatt-hour scale is entirely different. For example, the nuclear-powered German merchant ship Otto Hahn was deactivated in 1979 not because it did not work but because ports refused it to enter. Changing ship propulsion designs to run on green fuels is part of the solution, but caught in a catch-22: Port operators will not invest fuelling and bunkering capacity, and energy companies in the creation of these fuels, until the number of ships requiring it will increase, and ships will not be build to need those capabilities until they are available. The Center facilitates pilot projects and supports the creation of "green corridors" along major global shipping routes to break this knot.

While fundamentally, technology maturation is "only" relevant to creating low-risk investment choices, prioritisation, coordination, and transparent progress reporting on technology developments regarding ships, ports, and fuels is a massive challenge and bottleneck that the Center addresses.

Developing and Coordinating Industry Leadership: Global Teams for Global Challenges

While decarbonisation is an apparent competitive issue, it is also a shared societal responsibility. To increase the efficiency and effectiveness of innovation activities, competitors and supply chains have to work together. The Center facilitates industry leadership beyond current legal and regulatory mandates to level the playing field and remove disincentives from implementing lower carbon shipping capabilities. It also facilitates the exchange of innovation pilot insights and provides access to global experts for such pilot projects. For example, the Port of Rotterdam in the Netherlands has embarked on a pilot project to create infrastructure for the use of green ammonia fuel. The lessons learned on how to handle such a chemical safely in a busy port environment will be significant for all port operators and an essential building block for the deployment of this green fuel.

As part of Mission Innovation, the Center supports the creation of public-private partnerships. For example, public funding is necessary to mature high-risk – high-benefit technologies that are not yet attractive for industry-only development.

Regulatory Incentives: Green Transformation Requires Green Rules, Globally

The reason that current shipping has the carbon intensity that it has is that this system is the best choice for investors with the given technological, economic, and regulatory incentives. While technological advancement alone may eventually lead to low carbon technologies that are entirely competitive on their own, regulatory changes are required during the transition phase, where global economies of scale cannot be leveraged yet. For shipping, this poses unique challenges, as it is a truly global industry. No one body can pass binding regulation in the scope necessary to support ship design, fuel choice, port infrastructure development, and energy supply chain transformation. The Center facilitates global coordination in this space. It also concretely supports, for example, EU legislation with deep expertise on the economic and technical aspects of global shipping.

The Center's Core Competence: Making Uncertainty Workable

Any development with a 2050 goal will face significant technological, economical, and political uncertainty. The Center embraces this uncertainty in two ways: First, it invests significantly in modelling and simulation efforts to analyse future scenarios considering technical developments, competitive industrial aspects, policy and regulatory developments, public-private partnerships, financial sector developments, and customer preferences. While this does not reduce uncertainty, it does make it tractable for stakeholders. Investors, for example, better understand the sensitivities of future economic attractiveness of different solutions. Technology companies can investigate the co-dependence of technologies with regulatory and economic developments, and so forth.

Secondly, the Center actively engages in risk reduction activities. They are the most obvious in the technological arena, where the Center is involved hands-on in technology demonstrators to increase and prove the maturity of larger industrial applications. But they also include engagements with regulatory bodies to clarify what can be expected of future regulatory changes.

Implications: Changing the Global Shipping Engineering System: Building Trust in a Global Stakeholder Community

At the end of the day, the key challenge is that the Center must both aggressively support a decarbonisation agenda and maintain its status as a trusted advisor to all. It emphasises its independence and neutrality, which is greatly supported by its financial independence. This is expressed in its fact-based, technology-agnostic approach to setting the transformative agenda. It is that ground-level understanding of technical, economic, and regulatory realities that the Center offers to all stakeholders willing to work together to decarbonise shipping.

This is a truly trans-sectoral and interdisciplinary effort (see Fig. 13). The Center takes an Engineering Systems perspective by addressing technical and energy challenges, as well as societal, regulatory, and economic challenges. The corresponding interventions as a transition strategy that engages all stakeholders along the complex energy, design, and operations value chain of the shipping industry.

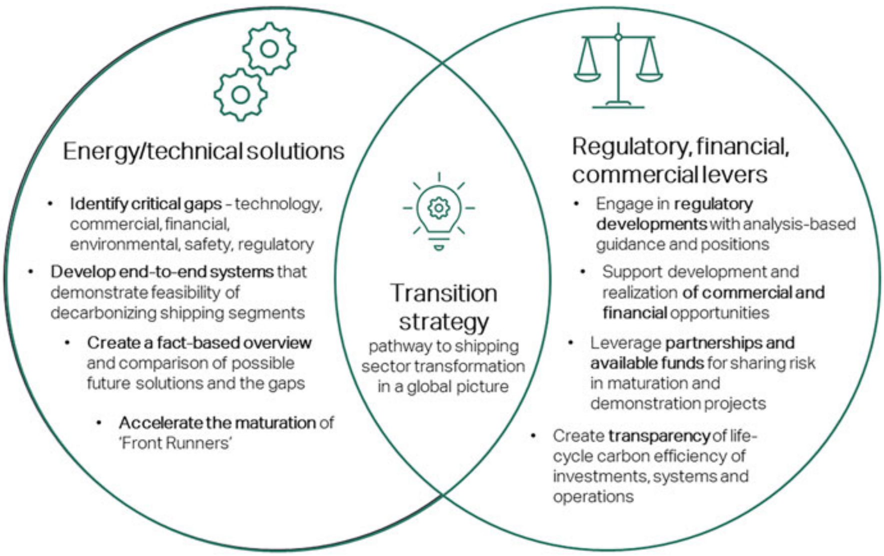

Fig. 13 The sociotechnical transformation agenda of the Center. (Internal figure, Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, used with permission)

Reflections and Conclusions

This short case of Mærsk's programme to decarbonise shipping offers several insights into the intervention design of engineering systems.

Engineering systems can be organised in networks without a central design position. The shipping system is a great example of an engineering system that has evolved and today isn't governed by a privileged position in a hierarchy. Instead, numerous private and public stakeholders maintain influential positions in the network of the system.

Transforming engineering systems requires mobilising (global) stakeholders aligning interests for collective action. Since none of the actors in the system holds a position enabling top-down regulation, the transformation relies on engaging stakeholders in building an industry-wide strategy that leverages technological, economic, and regulatory changes.

Creating evidence and transparency on the current (and future) performance of systems and solutions. Data is crucial in supporting the transformation of the shipping system. It is key in the top-down process establishing the global case for actions for the overall sector performance of like the contribution to global warming. But it also drives bottom-up initiatives developing business cases de-risking investments.

Identify, prioritise, and realise a programme of projects driving the transformation of the system. The actual decarbonising of global shipping operations is realised in a programme that combines top-down and bottom-up initiatives, often in the form of projects. Thus, the ability to identify, prioritise, and realise projects is key to reaching the centre's goal to "infuse confidence to act in time" globally in public and private actors.

Acknowledgements

This vignette on the activities of the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping is based on publicly available information as well as conversation interviews between Josef Oehmen, Jan-Christoph Napierski, and Søren Skovgård Møller. While every effort has been made to ensure accuracy, the case description is not an official policy statement by the Center.

Case 4: Prototyping Future Urban Transport Systems

A Case on Testing Autonomous Busses from Hospitals to Cities

See Fig. 14.

This case explores opportunities, complications, and deployment of efforts of tremendous scale to upgrade the transport legacy system in urban areas. Driven by the desire to create liveable and sustainable cities and having the fast-developing technology of driverless autonomous vehicles, the intervention to the legacy system

Fig. 14 Autonomous tested by the public transport provider Movia in Zealand's University Hospital, Køge, Denmark. (Picture: Ulrik Jantzen, used with permission)

has been set in motion. We are witnessing the beginnings of redesigning and transforming urban mobility. Driverless cars and busses have become a reality and already drive in test regimes in some European and US cities areas. This case draws on activities taking place in Denmark and describes the insights and knowledge gained from tests with autonomous busses.

Introduction to the New Transport System

The transformation of urban mobility is driven by the desire to achieve goals such as less congestion, reduction of CO_2 emission, air pollution, noise and costs, energy consumption, and improvement of road safety. Access to affordable and convenient transport for all is another goal, as access is far from being equitable. Besides this, the new transport system should contribute to the more ambitious objective of keeping the global increase in average temperatures well below 2 °C. The contribution can be rather significant, as "*transport accounts for more than half of global oil demand, making it a key contributor to climate change*" (Jørgensen et al. 2019). In short, the ultimate goal is to create liveable and sustainable cities.

To achieve the goals, or even to get closer to them to a "satisfying distance," is tremendously costly and requires deep involvement and collaboration of researchers, innovators, authorities, legislators, industries, transport users, and the public as a whole.

The measures required to start moving towards the goals are those formulated in the International Energy Agency's Sustainable Development Scenario and broken down into three distinct areas (Jørgensen et al. 2019):

- Avoiding and reducing travel activity
- Shifting to more efficient modes of transport
- Improving transport technology, fuel efficiency, and infrastructure

The advent of driverless autonomous vehicles (AVs) presents a unique opportunity for making the sustainable development scenario true and for a fundamental change in urban mobility. The envisaged new transport system will have a great influence on urban planning and how cities will develop. The design of the new system will redefine the public space, change people's behaviour, and possibly lead to healthier and greener cities. However, the design process has only been launched, and as the scale of foreseen changes is tremendous, it will take years for the technology and system to mature, and we do not know yet which of the anticipated scenarios will become the one in which we will live.

As stated in the International Association of Public Transport's Policy Brief (UITP 2017), it is possible to take citizens to their destination with at least 80% fewer cars. AVs have a great potential for providing much safer roads, fewer vehicles on the road, regaining urban space, lowering the cost of building and maintaining roads, and generating less noise. *"But this will only happen if AVs are introduced in fleets of driverless shared autonomous vehicles of different sizes reinforcing an efficient high capacity public transport network supporting walking and cycling"* (UITP 2017). At present, we can predict three basic scenarios for the new transport system with AVs, as seen in Fig. 15. Only fleet cars integrated with traditional public transport services can provide sustainable and better mobility and equity. This scenario will become true if the vehicles are fully automated, which means that AVs are classified as belonging to either automation level 4 or 5 according to SAE's classification (SAE 2016). Level 5 is the highest and referred to as "full driving automation;" while level 4 is called "high driving automation," and the difference from level 5 is that the operational design domain is limited, while for level 5, it is unlimited.

Passenger car manufacturers, transport and technology companies, and new automotive start-ups champions shape the market of future transport systems and the rapidly growing industry. Mass-market penetration will not happen overnight, as manufacturers have to collect a massive amount of data for machine learning technology to ensure a high level of traffic safety, passenger comfort, and public acceptance.

It is not only the technology that is still maturing. Research, modelling, and testing are concurrently being carried out and deployed on many aspects relevant to the new system to make it acceptable and successful. Tests take place in real urban environments and their results pave a way to a better understanding of what interventions to the existing legacy system should take place and what consequences we can expect. The tests are small-scale prototypes that are thoroughly studied to

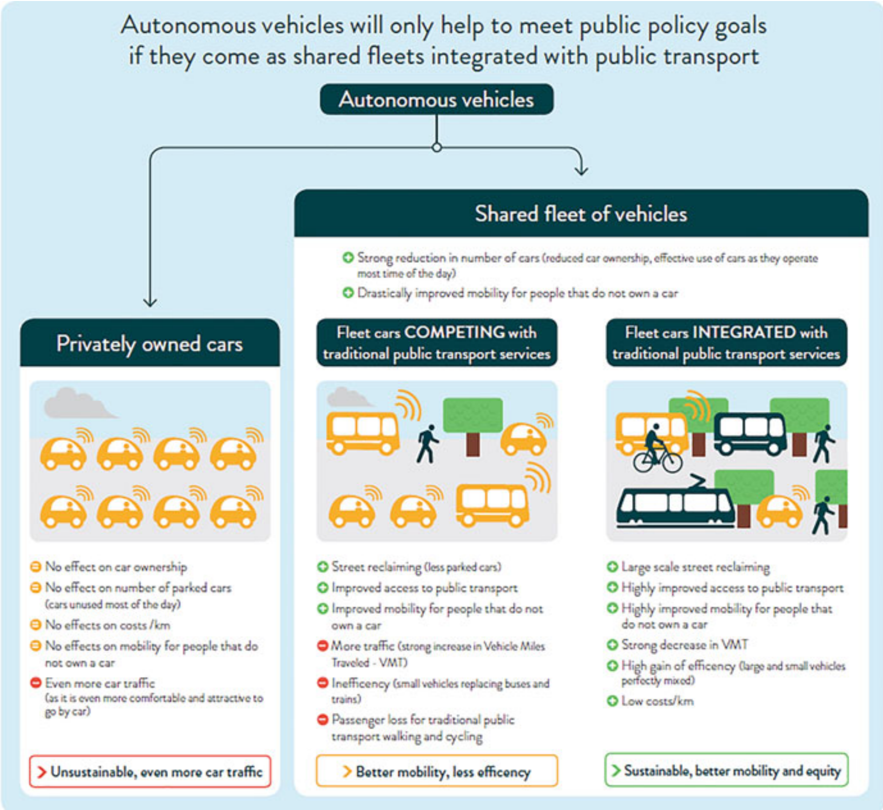

Fig. 15 Future basic scenarios for the new transport system. (Illustration copyright UITP, used with permission)

bring us closer to the system embodiment. In this described case, we will learn insights and knowledge gained from tests with autonomous busses taking place in Denmark.

Complication: Increasing Pollution, Immature Technologies, and Behaviour Change

Exciting opportunities come, as usual, with new risks and challenges that can hinder or break the mass introduction of the technology. Some pessimistic developments maybe those as smaller AVs weakening public transport services, low occupancy of AVs resulting in an increased traffic volume, lack of public acceptance, resistance against the reduction in the number of driver jobs, etc. The variety and uncertainty of future scenarios are much greater for shared fleets of vehicles where privately owned cars coexist and are integrated into one transport system with autonomous public busses and other transportation means. It might be that the transitory period from driver-driven vehicles to AVs will stretch over a longer period, as a mixed traffic environment has larger complexity than the environment having a more homogeneous fabric. People will have first to adjust their behaviour to hybrid environments and then to a more homogeneous environment with dominating driverless vehicles.

As mentioned in the Introduction, the full potential of the new transport system in urban areas will only be realised if autonomous private and shared cars are integrated with autonomous public vehicles. That is, autonomous busses must become another key player in the new transport system. However, their development and deployment do not go the same pace like that for passenger cars. Unlike autonomous passenger cars, large bus manufacturers like Volvo, Daimler, Man, and Mercedes have not deployed a noticeable production and large-scale testing of the busses. It is primarily small manufacturers who have started testing this type of public transport.

The design of the new transport system in urban areas is an example of a drastic intervention to the legacy system. It is accompanied by tremendous complexity, continuous development of technology, learning human behaviour of all traffic users, satisfying their needs, building new infrastructure along traffic lines, changing legislation, and others. All this poses plenty of questions not only to experts in technology but also in human sciences. Social and cultural aspects of the design of AVs become as much important as technological and even perhaps more important than technological aspects. *"Social scientists say the cars raise complex ethical issues"* (Maxmen 2018) and *"ethics for robotics and autonomous systems is a rich, complex multi-disciplinary concern, and perhaps more complex than many other ethical issues facing society today"* (UK-RAS 2019).

AVs can operate independent of human control, but they are designed by humans and should be viewed as "moral machines" in themselves. Artificial intelligence, part of the functionality of which is machine learning, can introduce ethical problems, as it might be biased; and decisions made on the acquired knowledge can be unethical or even illegal if they are seen as discriminatory (Maxmen 2018). If, for example, AVs are trained on a specific ethnical set of images, they are more likely to fail to recognise other ethnical groups that will be at a greater risk.

All in all, this is the case of designing the engineering system where the high technological complexity is amplified by a multitude of road and transport users with their individual preferences for comfort, safety, environmental issues, available budgets, etc. The complexity, which changes dynamically, generates uncertainty that in turn cannot be resolved without incremental knowledge acquisition, behaviour change via technology communication, its acceptance, feed-backed improvement, change of legislation and possibly the rules of the road, and willingness to invest as the market becomes receptive to the new technology.

In our aspiration to achieve the objectives for the new system, and given what technology can offer, we envision now many future scenarios deviating to very different degrees from those three major scenarios depicted in Fig. 15. Today, we find ourselves in a situation where we are uncertain about the plausibility and consequences of future transport system scenarios and what eventually possible future scenarios and their side effects are.

Deciding which scenario should be pursued, the uncertainty is to be resolved for both the set of possibilities (feasible and practicable scenarios and their consequences) and the likelihoods of consequences given a scenario.

At large, the reduction of uncertainty on the two dimensions (set of possibilities and their likelihoods) can be achieved in two ways: by modelling and acquiring evidence-based knowledge. For transport systems, modelling can be of very different types: stochastic analytical or numerical modelling, including Monte-Carlo simulation, imaginary experimentation in the form of brainstorming, etc. However, modelling is not able to provide answers to a great multitude of questions. In many cases, it is only evidence-based knowledge that can resolve uncertainty; for systems in development, it is only testing that can fill the knowledge gap on many issues. This is especially prominent for the designed transport system.

Having all the above in mind (the goals, measures to achieve them and the coarsely envisioned futures), let us see what existing plans and activities are undertaken to set the transition to the new transport system in action. For this purpose, we have studied activities deployed in Denmark and interviewed mobility advisor Mads Bergendorf of the Movia company, the largest Danish public transport operating company and initiated projects on testing autonomous busses in different urban areas.

Solution: Testing for Envisioned Interventions Based on Self-Driving Vehicles

Movia, together with the Copenhagen Metro and Region H and Sjælland, established a consortium to test autonomous busses (ABs) in different populated areas. The tests will deploy as shown in Fig. 16.

As formulated by the consortium, the objective of the test is to secure that public transport will continue being a long-lasting, integrated, and competitive part of the future self-driving transport system. Having this overarching objective in mind, the following three goals are pursued by conducting tests with self-driving busses:

- Influence and shape development of self-driving technology in the public sector in Denmark.
- Establish a foundation of evidence-based knowledge and acquire hands-on operational experience.

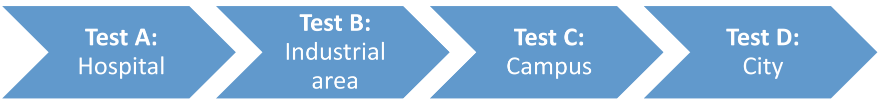

Fig. 16 Testing autonomous busses: project deployment

- Investigate, understand, and provide input to improving the technology regarding operational stability (driving precision and safety), economy, behaviour, and usability for different groups of users and their satisfaction.

Besides this, each test (from A to D) has specific learning objectives, and it is run until achieving these objectives. The duration of the test is not time-fixed but open-ended, which introduces an additional dimension of uncertainty associated with the allocation of the budget.

The first test, which has already taken place, was conducted in a closed hospital area in which the interference with other transportation means is limited and well-controlled. This testbed did not require strict permission by the authorities, which removes the uncertainty associated with legal issues. The start of the test was well controlled by the limited number of stakeholders involved.

Breakout Box: Key Characteristics of the Conducted Test

- 1 Navya Arma bus in operation
- 4 bus stops with ramps
- 375 m route
- 65 days of operation
- 8 h a day
- About 6.000 bus users
- 842 km driven in the period
- Maximal speed 3,6 km/t

For Test A, the following specific learning objectives have been set forth:

External

- Gaining first operational experience with driverless technology in a protected environment. (SAE level 3, conditional driving automation. An AV is capable of taking full control and operating during selected parts of a journey when certain operating conditions are met.)
- Gaining the first experience of bus users that are patients and visitors of the hospital. Two modes of operation: regular bus operation and operation on demand.

Internal

- Learning constraints and limitations the busses impose
- Acquiring experience with the establishment of the route and safety assessment
- Understanding what is required to establish test description and assessor’s report
- Collecting bus users’ experience concerning operation on demand
- Gaining the first experience with the assessment of service acceptance and human behaviour

All learning objectives for Test A have been fulfilled except for the operation on demand. The overall evaluation shows immense user satisfaction, high traffic safety, and reliable operation. However, it became apparent that the technology is not as mature as expected; frequent software restarts make operation impossible with the automation level 4; and the integration between Movia's system and the ordering busses on-demand was not achieved.

The expectation is that the technology will gradually improve, and it is not the main challenge the design stakeholders face.

There are several other challenges, and some of them are associated with legal issues that, in turn, can jeopardise the value of the conducted tests. For example, *"to be able to run a test on an AB, permission by the authorities must be granted. The permission is given to run a bus of a specific type, the specifications of which are stipulated in the application. The results of a test may become obsolete by the end of the test, as the technology may change on the way while substituting the old bus with a new one is a rather long and resource-demanding process"* (Bergendorf 2019).

As it appears now, the challenge we face is linked to human behaviour, values, preferences, sense of comfort, safety and equity, friendliness of the technology, ease of use, and the ethics of traffic users, along with ethical norms programmed in the controllers of AVs. What became clear during the test was that *"removing the driver from the bus does not only mean removing this functionality and handing it over to automated control. Removing the driver means removing many other functions from the bus such as information to passengers, an aid when qualified help is needed, handling emergencies, providing warnings and selling tickets. Another point, which is of great importance to pedestrians and other road users, is the absence of eye contact with the driver"* (Bergendorf 2019). This greatly influences whether there is common understanding and situation awareness among road users, which impacts comfort and feeling safe. *"The driver is the authority in the bus, and a solution should be found to substitute for its absence"* (Bergendorf 2019).

A test in which passenger-centred objectives will become the main focus is the one that is badly needed. That may significantly influence the design of the future transport system.

Implications: Possible Futures and Consequences Using Autonomous Vehicles

The very special conditions for running Test A (closed environment and very low speed) played a big role in achieving the positive evaluation of the results. While the conducted test was very limited, and the set-up was much far from the one expected in the future in a mixed and lively urban environment. It triggered active thinking about future lines of technology development, possible scenarios of the future transport system and illuminated challenges that need to be addressed in the following tests.

As any decision problem starts with shaping the possibility set (i.e. the set of choices from which alternatives will be evaluated), Test A has launched this process. Along with this, the assessment of the consequences of foreseeable alternatives got started. In this way, some undesired foreseeable futures can be made less likely, while favourable futures can be made having a greater chance of being true.

Figure 15 showed the large picture of the three future scenarios. Movia refines them and projects on possible futures where their roles can be different from those they have at present. The variety of scenarios is large. Mads Bergendorf gave a few examples that primarily concern new and possible business models, and three of them are the following:

Scenario 1. "As Mobility as a Service enters the market, companies operating public transport may appear redundant in urban areas. Municipalities, for example, could allow private companies owing ABs on some conditions provide the transport for public use."

However, the threat of this scenario is that *"the level of professionalism in operating the transport may drop, and, consequently, the safety may be compromised."*

Scenario 2. "Municipalities may want to contract a bus manufacturer directly. The role of the transport operator can be reduced to providing well-trained stewards that are employed at the operator company. In this case, the safety might be maintained on the desired level."

However, dispersed responsibility for operation can have negative consequences as well.

Scenario 3. "Municipalities may simply want to contract ABs on demand by having an appropriate app. Providing the required level of safety and comfort will become bus owner's responsibility. In this case, public driverless transport may become private like the taxi market, and it may be controlled by big capital funds like pension funds."

One of the threats is high and uncontrolled prices for ABs that can result in this transport means not being popular and even having more cars on the road.

The new technology will influence the way we plan to develop new cities and extend existing areas in the city. *"Urban planning carried out by professional groups of architects will redefine our public space, where people would like to live together. Perhaps we will not need much space for parking in the future, and the new transport system will contribute to solving the problem of urbanisation, as more and more people will move to cities"* (Bergendorf 2019).

When implemented, the new transport system will change our society, where the freedom of mobility is one of the futures. There is a political aspect in all this, as change concerns what society we want to live in, in the future. *"The design of this new engineering system may change our society, and in this view, it demonstrates how important engineers are in the society"* (Bergendorf 2019).

Reflections and Conclusions

The new transport system is an example of the design of an engineering system. Here the social and technical complexity and uncertainty about an abundant array of issues are interwoven in one tight clew, in which ethical issues and sustainability considerations have a great influence on how urban mobility will look in the future. If offers numerous learning point for engineering systems design.

Designing engineering system requires a holistic sociotechnical perspective. An obvious takeaway is that the new transport system – as any other engineering system – cannot be designed by simply applying technology. The growing complexity amplifies the importance of the sociotechnical perspective of engineering systems. "The very sociotechnical factors that make dealing with engineering systems so challenging also contain some of the elements of success" (de Weck et al. 2011). That is to say, the need for the new system is a human want to be triggered by the issues urbanisation brings and the capabilities of technology that may resolve these issues.

Prototyping interventions at various system levels through a lineage of projects. What is worth noting is that creating full-scale and end-to-end prototypes is not possible for engineering systems. Neither a full-scale simulation is an option. Consequently, a reductionist approach is employed, which often helps gain new knowledge about the system's behaviour. However, interactions between decomposed elements are ignored and, as a result, discovering emergent behaviours becomes hardly possible. The option left is smaller-scale testing and, by this, incremental knowledge acquisition. This is what we have learned from the projects being carried out in Denmark.

Intervening in systems creates benefits but also new risks. The new transport system can both positively and negatively impact safety. It is believed that AVs can improve road safety by reducing or removing human errors as an accident cause. However, recent accidents with AVs in the USA have shown that the technology can also cause fatalities. Safety risks and other risks will be redistributed compared to the current risk landscape in the transport system. As AVs are designed and operated by organisations, they will become risk bearers, and depending on a future scenario, the distribution of risks is uncertain at the moment as well. This, in turn, leads to the other issue of assuring AVs. Gaps in assurance and regulation, if not properly resolved, *"might lead to unsafe systems being deployed (if the regulatory regime is permissive) or safe systems not being deployed, thus losing potential benefits (if the regulatory regime is restrictive)"* (UK-RAS 2019).

Cross-References

► Architecting Engineering Systems: Designing Critical Interfaces
► Data-Driven Preference Modelling in Engineering Systems Design
► Digitalisation of Society
► Engineering Systems Design Goals and Stakeholder Needs
► Engineering Systems in Flux: Designing and Evaluating Interventions in Dynamic Systems
► Ethics and Equity-Centred Perspectives in Engineering Systems Design
► The Evolution of Complex Engineering Systems
► Transitioning to Sustainable Engineering Systems

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Public Policy and Engineering Systems Synergy

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Sebastiaan Meijer, Karol Olejniczak, and Jayanth Raghothama

Contents

Abstract

Engineering systems cannot be seen separate from the context they work in. Increasing complexity of society makes that larger systems no longer just concern technical aspects but include social and even societal aspects. Particularly, the societal aspects can be subject to public policy as a part of engineering systems design. This chapter provides a discussion of the nature of public policy

S. Meijer (✉) · J. Raghothama
Department of Biomedical Engineering and Health Systems, KTH Royal Institute of Technology, Stockholm, Sweden
e-mail: smeijer@kth.se; jayanthr@kth.se

K. Olejniczak
Institute of Social Sciences, SWPS University of Social Sciences and Humanities, Warsaw, Poland
e-mail: karol.olejniczak@swps.edu.pl

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and the role it plays in engineering systems, as well as the role that engineering systems methods play for public policy design.

The mutual relationship is positioned in a historic overview, where particularly the role of participatory methods has grown over time to capture human complex thinking in a world dominated by mathematic modelling approaches. It positions engineering systems to encompass public policy as an integral part of design, so that the traditional divide between engineering and societal contexts can be bridged.

Keywords

Behaviour · Engineering systems · Games · Government · Modelling · Policy design · Public policy

Introduction

Designing engineering systems will at some point always include designing policy. Policymaking and public policy is a well-established professional and academic domain. This chapter illuminates some key concepts that are highly relevant from the perspective of engineering systems design. One way of viewing is to position public policies as interventions that are available to the range of tools for an engineering systems designer. In other words, public policies may be seen as a way of intervening in socio-technical systems, as a leverage point for systems change (Meadows 2008). However, since the agency of public policy mostly lies with politicians, and the design of these policies traditionally falls within the logic of administrative planning, we pose a second way of looking at it to consider an engineering systems approach to the design of public policies. Systems do not operate in a vacuum, but in a societal context. The difference between the two viewpoints is in the role of the public policy: is it an integral part of making an engineering system work, or is it the object of an engineering systems approach itself? In this chapter, we explore the mutual relationship between public policy and engineering systems design and provide an overview of relevant policy theories and initiatives.

The Importance of Public Policies for Engineering Systems

Can you fly a Boeing 787 or an Airbus A380?

Such a simple question is impossible to answer. Because it entirely depends on the perspective of the person answering on whether this question would be interpreted as:

(a) Individual skills perspective: are you a qualified pilot?
(b) Technical engineering perspective: is such machine functioning safely as an aircraft?

(c) Consumer perspective: can I buy a service that uses this aircraft?
(d) Policymaker perspective: should we allow these aircraft in our airspace?

What this rhetorical question shows is that while aircraft manufacturing is an environment in which engineering systems methods have been matured and are the essential paradigm through which safety is guaranteed, the functioning of these complex machines in society is also embedded in other systems. For consumers, there needs to be a system of airlines that operates these aircraft on routes to even be able to use them. For the actual flying, the public policies, from aviation rules to environmental and noise policies, need to be in place to even be allowed to operate.

Engineering systems function within a context. And with the increasing technological intertwining of society, this context is becoming more and more complex. Understanding the impact of public policies on the use and functioning of the engineering system itself is therefore an essential skill in the engineering skillset. This chapter therefore takes the position that engineering systems will increasingly depend on and be affected by public policies. It is essential that the designers of the engineering system can design the necessary policies to fulfil the function intended of the system.

But how do policies come about? While for the public domain in democratic societies the decision power is in the hand of politicians through the various mechanisms of representation, most of the actual policymaking is done by policy professionals. The system by which policies are constructed is a design system itself and can be seen through the lens of engineering systems. While maybe not entirely new, this understanding is a break from the administrative evidence-based policymaking logic that is common. The designers of engineering systems become de facto designers of policies which traditionally were the domain of public administrations.

The Importance of Engineering Systems Approaches for Public Policies

With increasingly intertwined infrastructures and connected economies, public policies are becoming more and more complex to formulate. Our world is quickly changing, and we live in an era of long-term crises that even have systemic interactions with each other. The cascading effects of a change in one area are hard to predict and require careful consideration.

Engineering systems methods are tools to provide a systemic assessment of these cascading effects. At the same time, they are rooted in a “closed world” of traditional engineering, where the policy domain is inherently an open world in which anything can be introduced. Nonetheless, there is emerging evidence that system engineers can, when teaming up with public policy experts, contribute to the current challenges of public policies. In this perspective, the administrative domain remains the principal of the design process and engages engineering systems experts.

We claim that recent developments in both public policy theory and practice, including emerging complex policy issues, create an exciting opportunity for engineering systems in contributing to the improvement of the effectiveness of public policies and, ultimately, to the wellbeing of modern societies and communities.

Aims and Structure of the Chapter

When addressing a broad topic like this, it is always a challenge to be sufficiently inclusive to related areas while also aiming to have sufficient depth to get further into the matter. Therefore, in the first section of this chapter, the authors aim to introduce to the reader the main concepts of public policy: explaining its purpose, focus, process, and evolution of the research on public policies, as well as discussing in more details its logic and toolbox applied in public policies. Based on this overview, the authors identify key areas for potential contributions from engineering systems as a field. The remaining sections of the chapter go over the history of engineering systems methods pointing out how they could help public policies in the identified key areas.

Public Policy: A Brief Overview

Purpose and Content of Public Policy

Public policy, in the shortest way, is "what governments choose to do or not to do" and what difference it makes (Dye 2017). Governments' (in)actions can be driven by political, moral, and economic reasons (Theodoulou and Cahn 2013).

Specific public policies deal with problems that are usually complex, emerging at the intersection of ecological, social, and technical issues; they are often wicked and ill-defined or framed in a way that reflects more the perspectives of the stakeholders than reality. In fact, often even collective objectives and contents are not agreed upon and decision-makers operate without clear criteria of an "optimal decision" but rather with an approximation of some understanding of needs and interests of different actors (Migone and Howlett 2015).

Furthermore, the underlying challenge of specific public policies is understanding of human behaviours. Even policies as that may appear as relatively technocratic or "hard" will ultimately be influenced by behaviours of the individuals and organisations involved (Peters 2018, p. 9). The behaviours of actors are shaped by their bounded rationality and complex socio-ecological interdependencies and they evolve over time. Thus, understanding of the behaviours of policy subjects, what drives them, and what makes policy actors comply is a vital challenge for designing effective policies (Soman 2017; Weaver 2015).

Due to these two peculiarities – the complexity of public issues and mechanisms of actors' behaviours – the probability of success is far from 100%; policy problems can be ameliorated rather than solved; they need to be constantly revisited over time, while new solutions are usually built upon earlier efforts. That is why the classical scholars call public policy a "tireless tinkering" (Wildavsky 1987/2018) and a "science muddling through" (Lindblom 1959), underlying its incremental character and difficult consensus building around policy options.

In the policy process, the dominant framework used for analysis is the so-called "stagist" or stages-heuristics model (Colebatch and Hoppe 2018a; Howlett 2011; Theodoulou 2013). It is depicted in the form of a cycle. Although individual authors offer slightly different names for each stage, we can broadly distinguish five main elements of the cycle: agenda setting, policy design (also called policy formulation), policy implementation, evaluation, and policy change.

Agenda setting refers to setting a contextual list of actionable governmental priorities, i.e., issues that are recognised "to be the most important and that need to be urgently addressed" (Zahariadis 2016, p. 5). The dynamics of things emerging on the agenda is far from a rational process of prioritising collective needs of society. Instead, it emerges from timing and combined dynamics among politics, policy options, and problems (multiple streams theory) (Kingdon 1995) or is a mix of policy issues raised by different actors that incrementally build up a dissatisfaction among stakeholders with the current status quo and open a window of opportunity for change (punctuated equilibrium model) (Baumgartner and Jones 1993).

Once the choice for action is made, a deliberate and conscious design attempt starts to create a response to a policy problem. The policy design stage integrates an understanding of the problem with ideas on intervention and the values that are being sought through the respective policy (Peters 2018; Birkland 2020). Empirical research shows that the prioritisation and problem-solving of governments is far from a fully rational model. Recognising the blindness to emerging challenges, it can be said (Baumgartner and Jones 2005) that highly disproportionate attention distribution and limited information processing shape proposals for solutions and choices of specific interventions.

Policy design is followed by policy implementation, that is, basically speaking, the delivery of the policy intervention (solutions and services), an operational strategy of changing inputs into outputs. In theory, implementation is a sequence of technical, day-to-day activities and institutional arrangements required to deliver the policy goal. However, in practice, as classics of public policy points out, the delivery system can drift far away from the initial ambitious assumptions and plans (Pressman and Wildavsky 1973).

The cycle is closed by evaluation and potential policy change. Evaluation focuses on assessing the worth and merit of public interventions and improving their positive impact over time (Shaw et al. 2006; Newcomer et al. 2015). Over the years, evaluation practice slowly moved from a focus only on accountability of effects toward providing evidence-based learning on "what works for whom and in what context" (Pawson 2013). It also started to apply more systemic methods to address those questions (Olejniczak et al. 2020a). The accumulation of evidence on how policy works (or not) combined with yet another window of opportunity can eventually lead to policy termination or change.

It has to be noted that the policy cycle is an abstract, ideal concept (Harguindeguy 2007). In reality, the policy process is much more iterative or even chaotic (Tyler 2013). However, the stages-heuristics model allows organisation of thinking about different policy activities and captures well the real-world dynamics that push for constant adjustments of solutions, making policy decisions temporary.

Public policy is not only a practical craft but also a field of academic reflection. Key questions raised by public policy researchers focus around four broad issues (Theodoulou and Cahn 2013; Birkland 2020):

1. How people and groups acknowledge and define problems?
2. How they seek and implement solutions to those problems?
3. Who is affected by those solutions?
4. What are the conditions under which policies change?

As we see these are practice-oriented questions. That is because the foundations of public policy as a research discipline have been formed by policy sciences literature of the 1950s, rooted in American pragmatism that treats research knowledge as a way of tackling social challenges (deLeon and Vogenbeck 2007). One of the founding fathers of the discipline – Harold Lasswell – defined it as an applied interdisciplinary study of the problems faced by government through a social sciences lens (Lasswell 1951). Since then, the core of policy sciences has been its problem orientation, multidisciplinary nature, ambition to use advanced theories and methodologies, and intent to remain value driven (Dunn 2019). This perspective has been strengthened in the late 1990s and early 2000s with the evidence-based policy movement that postulated a more rigorous and robust use of data and analysis in improving the effectiveness of policymaking (Nussle and Orszag 2015; Yanow 2007).

For years, policy analysis has been dominated by rational choice theory and the classical economic approach of portraying policy as a mainly economic activity of resource distribution by the government (deLeon and Vogenbeck 2007). However, in recent years, three research themes acknowledged that real practice substantially deviates from the classical economic model, offering a more fine-grained understanding of public policy.

First is the claim that government has been slowly supplanted by governance of self-organising networks (Bevir 2007). Although some authors point out that that claim is too strong in diminishing governments role (Colebatch 2018), it correctly acknowledges the move toward more collective action dynamics and coproduction of public services (Ostrom 1996). Various ways of involving citizens, consumers, and community organisations in producing public services become a visible trend in public policy (Nabatchi et al. 2017).

Second is the emergence of behavioural insights providing a more realistic view on both policy designers (Hallsworth et al. 2018; Dudley and Xie 2019) and policy addressees' decision-making under uncertainty, namely, recognition of their bounded rationality, willpower, and self-interest (Shafir 2013; World Bank 2015).

This had substantial implications for the practice of public policy (Jones et al. 2013) (OECD 2017; Ruggeri 2018).

Third is the development in public policy literature as a mechanistic approach. It aims at unpacking the mechanism – the black box of factors and interactions that, when triggered by policy intervention, could eventually lead to policy effects (Capano and Howlett 2019). It builds upon earlier well-established literature on social mechanisms (Hedström and Swedberg 1998) and practices of policy and program evaluation (Astbury and Leeuw 2010). It introduces a useful distinction between first-order mechanisms (triggered by the intervention's application to affect individual policy actors) and second-order mechanisms (transforming the context of particular policymaking, that is, systemic policy learning) (Capano et al. 2019).

Summing up, we can therefore portrait public policy practice as a design and problem-solving activity that is a set of ongoing experiments made by governments, in cooperation with other stakeholders, with often inadequate information (Bardach 2006; Campbell 1998). This "tireless tinkering" aims to design and deliver new interventions that will trigger positive changes, address socio-economic problems, satisfy the demands of the citizens, and ultimately make the world a better place (Howlett 2011; Peters and Pierre 2006).

In the next section, we apply these recent perspectives to discuss the logic and toolbox of public policy. We focus on the first stages of the policy cycle (policy design) since this is the frame that determines the later stages. The proposed framework based on recent work of Olejniczak et al. (2020b) will link public policy with engineering systems, allowing to identify areas for potential synergies.

The Logic and Toolbox of Public Policy

Human problem-solving is a hypothesis testing effort. The word "hypothesis" is used here in a common-sense way, as simple heuristic – a supposition about addressing some aspects of the world around us. It has a basic association form: "*If* this is the problem, *then* this could be the solution". Developing and testing such hypotheses through observation, trial, and error is part of our everyday thinking (Evans 2017).

Public policies follow the same logic of problem structuring and problem-solving (Dunn 2017, p. 69). The problems are addressed with a designed response – an intervention undertaken by government or a coalition of different policy actors interested in policy issues. In public policy literature, the causal chain explaining how and why particular policy activities and resources could trigger positive change is called the theory of change (Chen 2005; Astbury and Leeuw 2010; Rogers and Funnell 2011). The theory of change is followed by the theory of implementation – a more detailed plan of how the change should be delivered in a practical, operational way (Donaldson 2007).

However, the collective nature of policies makes this sense-making challenging and fragmented. Participants of policy processes often approach policy issues with different perspectives and values. Framing policy issues is therefore a collective puzzlement among politicians and policy decision-makers as well as a spectrum of stakeholders. This often ends up with an incoherent theory of change or even with conflicting hypotheses on how things could be changed (Colebatch and Hoppe 2018b).

The *if-then* logic of the theory of change can be broken down into four sets of assumptions made by policy actors involved in the development and implementation of specific intervention (Olejniczak et al. 2020b):

1. The assumptions about the nature of the policy issue that frames the problem
2. The assumptions about the root causes of the problem
3. The assumptions of what policy intervention would be most effective in triggering the desired change
4. Assumptions about implementation

We discuss them briefly in the next paragraph with examples.

Framing of Policy Issues

Framing of a policy issue is partly analysis, partly negotiations, partly pragmatism. It means breaking down the broad policy issue (e.g., transportation and congestion in the cities) into specific policy problems that relate to behaviours of particular actors (daily commuters choosing public transportation instead of private cars) and the desired level of compliance – that is, envisioning the desired state – a situation when a problem is addressed. One policy issue can be framed in different ways and broken down into a number of specific policy problems. The matrix below allows mapping different options (Fig. 1). First, it distinguishes between types of actors that perform the behaviour. The difference is between individual behaviours (that means citizens) versus collective behaviours (of companies, public institutions,

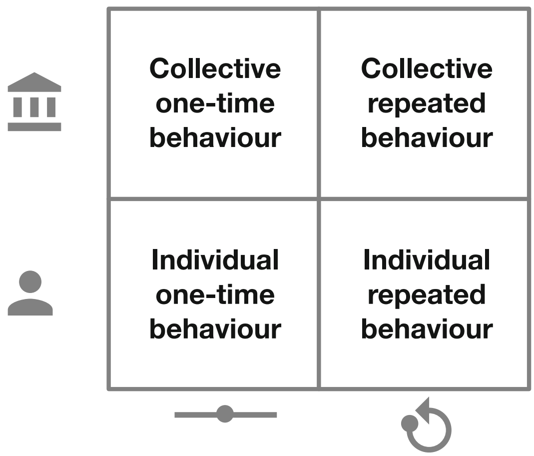

Fig. 1 A matrix for framing policy issues in behavioural terms (Olejniczak et al. 2020b)

groups of policy actors). The second dimension focuses on the character of behaviour – a one-time action (e.g., a single decision) or repeated actions (including habits and routines).

Consider the following recent example of a complex and urgent policy issue – a response to the COVID-19 pandemic. Governments' policies can be framed in a number of ways. First, governments are striving to slow down the exponential spread of infected cases (so-called flattening the curve). That focuses mainly on changing the behaviours of individuals (both in terms of one-time decisions and routines) related to anti-epidemic hygiene, mobility, wearing masks and social distancing. Yet, a number of governments also decided to target organisational actors (lockdown of businesses and cities) in order to ensure individuals' isolating themselves. Second, in the short term, governments are attempting to ensure that healthcare delivery systems meet demands. In the longer-term perspective, governments are trying to develop cures and vaccines against the virus. Both of those framings focus on institutional actors and their capacities for repeated or one-time behaviours. For this, governments are rapidly developing infrastructure, securing the availability of personnel, building networks of actors, and facilitating the deployment of medical equipment. Third, public agencies are starting to address the systemic disruption or even the risk of the failure of national socio-economic systems. This last area calls for policy tools of a macroeconomic nature. This frame covers all types of behaviours and types of actors. As we see from this example, a specific policy issue (e.g., the COVID-19 pandemic) is multifaceted and often needs to be broken down into a series of policy problems that are then tackled by specific interventions.

Assumptions About Root Problems

The second set of assumptions in the theory of change is related to roots of the problem. In other words, policy designers hypothesise what stops policy actors from behaving in an expected way. Going back to our example – what causes citizens not to wear masks and comply with social distancing requirements, or what hampers the capacity of hospitals in taking care of the inflow of COVID-19 patients. In recent policy practice, a simple heuristic has become popular in articulating these assumptions. It is called COM-B (Michie et al. 2011). It states, as in crime stories, that an actor in order to execute the behaviour needs to have capacity, opportunity, and motivation (in crime stories, means-opportunity-motive). Capacity could relate to lack of personnel resources (time, money, physical abilities), gaps in knowledge or skills to perform specific behaviour, or cognitive limitations (the spectrum of different cognitive biases and perceived agency). Motivation covers factors that drive policy actors to start and complete behaviour. The deficits in this category cover conflicting emotions or habits, cost-benefit calculation or specific attitudes and beliefs. Opportunity covers contextual factors such as lack of required infrastructure to perform actions, deficient setting or rules in the administrative environment, or even social influence that blocks compliance. This approach, introduced by Michie et al. (2011), is well grounded in the systematic review of behavioural literature (Michie et al. 2014).

Assumptions Underlying Tools to Trigger Change Mechanisms

The third set of assumptions relates to the toolbox that can be used to enable the behaviours of policy actors (make them behave) or as policy literature calls it matching policy interventions and their targets (Howlett 2018). The interventions (also called "tools") used by governments are extensive, and they consist of projects, programs, contracts, loans, charges and taxes, and regulations (Salamon and Elliott 2002). Public policy literature tried to organise the toolbox of government. The most popular arrangement of the government toolbox is the resource-based approach developed by Hood (1986). Policy tools are organised according to governing resources that are at the disposal of public institutions. The typology is called NATO as it stands for Nodality tools, Authority tools, Treasure tools, and Organisation. Additionally, Hood distinguishes between two types of use of those tools: effectors (that aim to change the situation) and detectors (aiming to analyse and understand a policy situation).

With the growing application of behavioural insights, a new typology has been emerging. It focuses on the *modus operandi* of different policy interventions in terms of the mechanism used to make policy actors behave. The early version of this approach is proposed by Vedung (1998) who identifies (1) "sticks", regulations that oblige policy addressees to behave (e.g., sanctioned rules, prohibitions); (2) "carrots", economic means that make the action easier or more difficult for policy targets by abduction or deprivation of material resources (tax, levies, delivery fees); and (3) "sermons", information tools by which the target group is informed about claims and reasons and persuaded to behave (communications, labelling, and audits but also demonstration programs and advice). This straightforward list can be extended by "fishing rods", that is, all aids that equip policy actors to perform the behaviour and "nudges" that means the restructuring choice architecture for policy actors in order to guide them toward preferable options but without forbidding any options or significantly changing their economic incentives (Thaler and Sunstein 2009; Sunstein 2017).

In policy practice, governments usually apply a policy mix of interventions to address particular policy problems. For example, pushing citizens to comply with the social distancing rule can be obtained with sticks (fines for being in public places), sermons (information campaigns about the risk of infection and ways of avoiding that by isolating itself), as well as removing opportunities (closing restaurants). That increases chances for effectiveness but at the same time complicates "hypothesis testing" that means establishing which intervention the positive effect can be attributed to.

Areas for Potential Contributions from Engineering Systems as a Field

We discussed public policy as a design-oriented problem-solving and hypothesis testing activity. As its core, policies are a set of interventions to regulate behaviours of policy actors – individuals and organisations. They are rarely "built from scratch";

rather they are developed on solutions already existing. This perspective allows us to identify certain challenges that public policy faces and where we see benefits from synergies with engineering systems.

In line with de Weck et al. (2011, e.g., p. 31), we perceive engineering systems as complex socio-technical systems containing engineered (sub)systems and which can be analysed from a functional perspective as well as a contextually embedded perspective. All the major backbones to our society like logistics, healthcare, and energy are relevant to perceive in the light of an engineering systems perspective. The context can be large in scale (global supply chains) but also by its complex intertwining with other (sub)systems, like in smart city projects. Engineering systems are characterilzed by challenges such as technical and organisational complexity, social intricacy of human behaviour, and uncertainty of life cycles and design cycles.

Unlike pure engineering problems, human systems, either social or engineering in nature, present unique challenges, including long time horizons, issues that cross disciplinary boundaries, the need to develop reliable models of human behaviour, and the great difficulty of experimental testing (Donaldson 2007).

The first potential area of contribution from engineering systems is helping to tackle the complexity of policy matters in a holistic way. That means analysing policy challenge but without chopping it into isolated problem silos. Policy challenges are configuration of behaviours of different actors that are embedded in broader environmental and technological context. Finding methods to approach this in a pragmatic yet non-reductionist way would be most valuable. Thus, engineering systems could help in better framing policy issues, in particular identifying systemic interdependencies and trade-offs.

A second area is unpacking the box of (non)compliance mechanisms. That means better understanding of multifaceted configurations among capacities, opportunities, and motivations that enable or hamper behaviours of policy actors. In short, engineering systems could help in identifying root problems.

The third area is testing and anticipating the effectiveness of hypotheses about specific policy interventions. As we pointed out, practitioners have a spectrum of tools that use different logics to trigger compliance mechanisms and induce behaviours among citizens or organisations. It would be most valuable to test a priori, in a safe environment, what mix of those interventions is most effective and efficient in getting policy actors to behave. In short, engineering systems could provide better and more timely insights into what works.

The final area is tracing the implementation of policies. The delivering of the solutions has become ever more complex and multidimensional, engaging coalitions of actors that need to be orchestrated. Engineering systems could provide some guidance on the coordination of complex processes.

Summing up, a current overarching challenge is to provide policy actors (decision-makers and stakeholders) with a safe space and method to articulate and test their rationalities and assumptions. As we discussed in previous paragraphs, public policy solutions are often built on hidden and unconscious sets of assumptions about the nature of the specific policy challenge, roots of misbehaviours, and ways of dealing with it.

Evolving Synergies Between Public Policies and Engineering Systems

Engineering systems methods in and for policymaking are not new, but the last decade has seen an increased interest in the use of these methods and the societal challenges posed by increasing complexity. Engineering system designers as policymakers and the use of (rational) engineering methods in the design of policies are two views that we can distinguish today but that should be understood in a historic context of development, industrialisation, and global challenges. There is no sharp distinction to make between when "regular" engineering interplayed with policymaking and when engineering systems perspectives became dominant, as the two co-evolved. In this section, we explore the quest of leading us to where the field is today, to provide some clues about where the future could lead us.

Optimisation and from a Whole to the Parts

For a correct understanding of the current status of the field, we need to start in the 1960s. The post Second World War economic boom, particularly in the USA and Europe, created unprecedented welfare and industry developed. Much of this was the result of a rationalised, industrial approach to manufacturing, coupled with societal policies to develop the middle class. During this era, the belief in *optimisation* of processes for the greater benefit to all was so firmly planted that it still resonates.

However, with a shift from pure manufacturing to the development of services and the rise of middle-class office jobs, the dominant organisational paradigms evolved from machine bureaucracies to professional bureaucracies and divisionalised forms (Mintzberg et al. 2020). The formation of the professional standard and doctrine as well as the reduction of richness in coordination to core tasks and simple indicators crept into society. Early scholars and policymakers who recognised the drawbacks for public systems were particularly triggered by what we now would call:

1. The use of the human intelligence for holistic thinking, to counter the post-industrial approach to humans as source of labour
2. Avoiding suboptimal partial solutions, to counter the increasing complexity of manufacturing, with the first waves of global manufacturing in sight in networked industrial complexes (Menard and Shirley 2005)
3. The advent of computing, promising ever-increasing power to solve large-scale problems

In the USA, the RAND Corporation was formed in 1948 to connect military planning with research and development decisions for public welfare and security. Particularly during the mid-1950s and 1960s, groundbreaking work in computer science, game theory, linear programming, dynamic programming, and applied economics was being done at RAND, giving more tools to the dream of societal optimisation. Just the number of Nobel laureates in economics associated with RAND during this era proved the influence of this engineering approach to the public sector. Much of this research became foundational for modern economic policies, particularly with game theory and dynamic programming for resource allocation. Yet, persons like Martin Shubik (1975) already experimented with the use of policy exercises similar to war games that were known from the military world to do early forms of scenario planning.

Global Challenges: Complex Models for Complex Problems

In the late 1960s and early 1970s, the looming ending of the world's resources (oil) and ramping environmental issues suddenly bolstered a second wave of engineering methods for policies. The concept of large-scale natural systems from ecology mixed with growing simulation resources started an era of large-scale systems simulation as a basis of policy planning. Apart from the still prevailing macroeconomic planning bureaus, also the basis for environmental modelling was born. Jay Forrester (1994, page 246) introduced system dynamics modelling, which, in his own words, "uses computer simulation to take the knowledge we already have about details in the world around us and to show why our social and physical systems behave the way they do".

However, Douglas Lee (1973) critically assessed this work and summarised his conclusions in three points:

- In general, none of the goals held out for large-scale models have been achieved, and there is little reason to expect anything different in the future.
- For each objective offered as a reason for building a model, there is either a better way of achieving the objective (more information at less cost) or a better objective (a more socially useful question to ask).
- Methods for long-range planning, whether they are called comprehensive planning, large-scale systems simulation, or something else, need to change drastically if planners expect to have any influence on the long run (Lee 1973).

Lee's insights slowly spread, and by the early 1980s, the number of large-scale comprehensive models used for policymaking reduced generally to the economic domain, environmental issues in isolation, and to a certain extent transport planning.

In this period, we recognise the wish to making designers of engineering systems the de facto policymakers, with a belief in rational optimality to find the solution (s) for global issues.

Agency Included: Participatory Methods

Meanwhile, several individuals experimented with the role of humans in the simulation process and with ways to engage policymakers with models and with each other. Richard D. Duke grouped people around him and formed the International Simulation and Gaming Association (ISAGA), which still thrives. While the gaming and participatory policy approaches were never very large, their maturity and use for critical policymaking grew steadily up to the mid-1990s. Igor Mayer (2010) provides a comprehensive overview article of this history. The rationale builds on the understanding that models can be used to understand complex systems but that both intelligence and agency lie with the representatives of the institutions designed to govern.

In the mid-1990s, things suddenly changed. The penetration of low-cost computing and popularity of computer games suddenly started providing momentum to the engineering systems-related modelling and simulation work. It became possible to build simulations and (serious) games that allowed for experimentation by stakeholders and by newcomers to a field.

Experiential learning, as advocated by Kolb (1984), got a boost with simulation and game-based learning (Alfasi 2003; Bekebrede et al. 2015; Tan 2014). While most of this stayed in classroom settings, some work actually strongly influenced policy, thereby enabling the engineering systems approach to a participatory approach to public policies.

Particularly worth mentioning here are a number of streams, including the following:

1. Several groups attempted the governance of natural resources and commons with agent-based models and games. The CORMAS community (Barreteau et al. 2001) supported local policymaking in rural communities, much in line with the work of Ostrom (Ostrom et al. 1994).
2. Governance of supply chains, particularly of food, but also other critical supplies, has been studied, as extension to the existing supply chain simulations and games that focus on technical and economic efficiency only (Hofstede et al. 2006; Zúñiga-Arias et al. 2007).
3. A large set of methods and initiatives exist around climate change, where some are actually used to engage stakeholders in the formation of public policies (Parker 2006; Petersen 2012). A subset of these handle the energy transition for which interactive planning support systems have been used extensively (Flacke et al. 2020).
4. In transportation, several approaches exist (for a review, see Raghothama and Meijer (2014)).
   (a) Tools like Aimsun and PTV Vissim now provide interactive visualizations with multiple alternative parameters for interactive decision-making with experts.
   (b) The Dutch railways have pioneered their transition to high capacity rail using engineering systems approaches enriched with gaming and simulation (Meijer 2012a, b; Van Den Hoogen and Meijer 2016).
5. In healthcare, the human-focused engineering systems approach expanded as a natural extension to clinical training centres (Kato 2012; Zhang et al. 2018, Savage et al. 2017).

While the examples show a great variety and high levels of success of the participatory approach to engineering systems in public policies, the general breakthrough seems to be difficult to achieve. Successful change in socio-technical systems requires active participation of a wide range of people in the modelling and policy design process, people who often lack technical training. The inherent increasing complexity in policies also leads to new large-scale models, particularly around climate change, however with a different approach to dimensionality than earlier (Moustaid et al. 2020). Still, the same questions appear: how do we deal with open versus closed systems, and how do we understand feedback loops that can be interpreted pluralistically?

Such questions are not recent and have been discussed from both engineering and policy perspectives (Balducci et al. 2011). The conceptualisation of so-called wicked problems (Rittel and Webber 1973), problems that cannot be defined clearly that have no definite start or end nor a clear owner and ultimately no solution, was embraced as representing fundamental uncertainties in a complex world. New approaches to modelling followed, with more complex monolithic models, layered models that build upon previous approaches, and integrated models that sequence input and output and interact among each other (Raghothama 2017).

Current State: Layering Methods and Simulations

With the increase of computing and the current era focus on the power of data analysis and artificial intelligence, a layered approach appears to make use of different engineering methods for sense-making in public systems (Fig. 2).

Simulations and models are now a critical scientific instrument, representing a new method of doing science, besides theorising and experimenting. Simulation in scientific practice and the role of simulations in science and policy have raised enormous potential to understand complex systems as well as a host of philosophical and epistemological issues. Simulations make it possible to "experiment" with theories (Meijer et al. 2014) in new ways as well as allowing computations that were hitherto unfeasible (Grune-Yanoff and Weirich 2010). They also perform other functions, such as exploration, negotiation, and communication. Therefore, the engineering system value for public policymaking increased, particularly when focusing on the structured involvement of stakeholders through methods like gaming (Grogan and Meijer 2017).

Simulations function as mediators between theory and reality. Constructed in part from either or both theory and data, simulations are nevertheless autonomous agents that facilitate learning about reality (Morgan and Morrison 1999). This mediation is analogous to Duke's multilogue, simulations when applied for policymaking also function as mediators between actors and between actors and reality (Duke and Geurts 2004). The reflexive capacity of humans adds a qualitatively different source of unpredictability to simulations (Petersen 2012). The simulations' role as mediators in actor networks and between actors and reality changes the nature and function

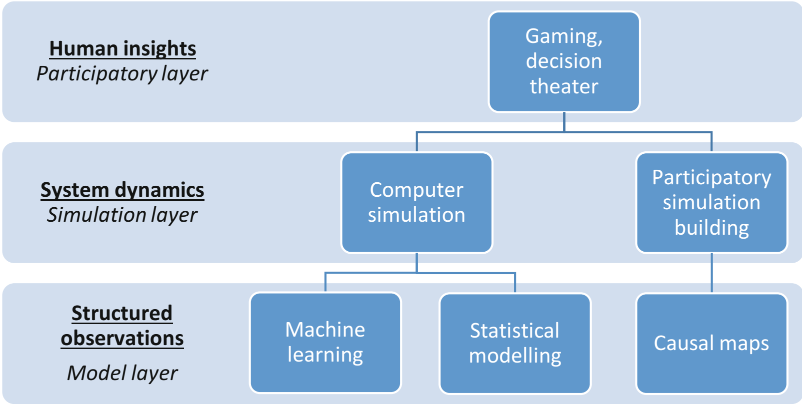

Fig. 2 A layered approach of engineering systems methods in public policies

of models and simulations in policy studies, in turn affecting their representation of the reference system (Knuuttila 2005).

A model can represent a system through varying degrees of realism or similarity (Giere 2004). Policymakers and scientists are typically interested in the dynamics of systems, an emergent property of the interactions between subsystems, and the behaviour of a system over time (Grune-Yanoff and Weirich 2010). In gaming, or in participatory modelling, we are interested not only in the representation of a complex system in a model but also the interpretation of this model by an actor, especially if the actor is a policymaker (Giere 2004; Grune-Yanoff and Weirich 2010; Morgan and Morrison 1999).

Representation is typically defined as the degree of correspondence or similarity between the mode and the reference system (da Costa and French 2000). This triadic relationship between models, actors, and reality is represented in Fig. 3. The representation is not only a relationship between theory and reality but also involves the users and their interpretation of it. It is a relationship where the actors reflexively learn about their (own and other actors') interactions and relationships with the reference system (Giere 2004; Knuuttila 2005). Here, models and simulations mediate (as autonomous or semi-autonomous entities) between users (in the case of policymaking actors, either institutions or otherwise) the theoretical foundations which form the starting point of a model and the real system that model references (Morgan and Morrison 1999). This mediation allows experimentation and exploration but, more importantly, delegates the referential power of the model to the users.

Simulation games, however, address policy issues in complex systems through a combination of a scientifically responsible model and control of other confounding factors arising from the problem context. Building simulation games is a design activity and by nature involves a significant modelling enterprise, which could focus either on the technical-rational components of the system or on modelling the actor networks of the system (de Bruijn and Herder 2009). A recurring question in this modelling activity is one of drawing the system boundaries.

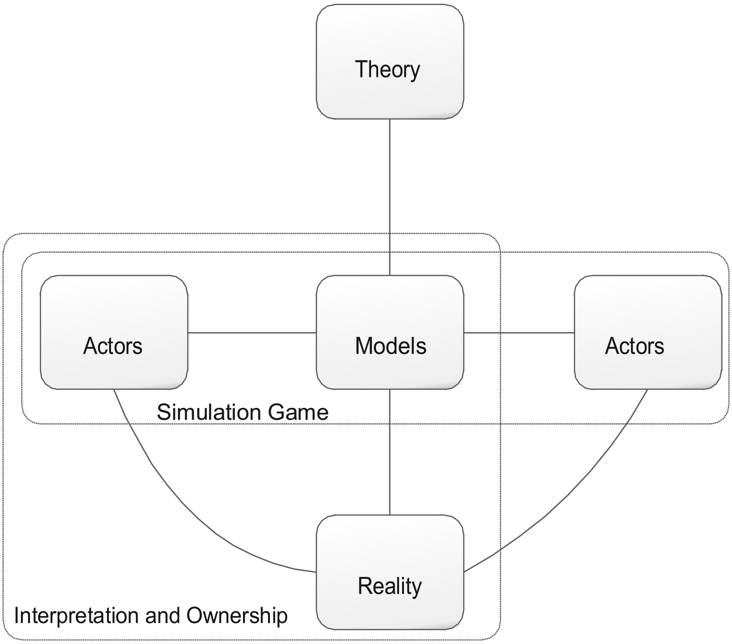

Fig. 3 Triadic relationship of representation

The traditional systems engineering methodology of developing models and simulations privileges and prioritises the modeller's intentions over the users. The design of gaming where any form of real-world physical reality needs to be incorporated is concerned primarily with the design of the game, making it a strongly artefact-centric approach. The influence of the game designer, their backgrounds, the purpose of the game, the rules and conventions of the relevant domains, and scientific disciplines all contribute to the game design. The designer has to make key decisions along the game design process of including or excluding system components, of including them through various abstractions, or including them at different levels of fidelity (Raghothama and Meijer 2018).

To allow effective interaction with the model, the game needs to model the reference system effectively. Traditionally, this requirement was interpreted from an engineering perspective, where the model was developed to be scientifically accurate and validated. However, from the perspective of the model as a mediator, in the process of the social construction of the model, there are additional requirements which stem from the context of use of the model.

The emergence of all of these methods, of interactions with models, and the rise of evidence-based policymaking points to one clear, major issue: that we are long past the logic and certainty of "analyze, predict, and plan". This engineering approach fails in the face of unprecedented complexity and uncertainty. The efforts to mitigate this, through pluralism and participation, are essentially vehicles that open up policymaking to embrace uncertainty and ambiguity, instead of mitigating it. This would require an extension of both the participatory and large-scale modelling turns, to include "the other experts" in the room – all the sorts of expertise that are useful in seeing follow-on effects – to collectively grasp the complexity of these socio-ecological systems. But for these attempts to be accurate, we also need non-experts – not just for "social legitimacy," or for normative reasons, but to actually see the impacts of the interventions in various contexts (Buck 2019).

A policy intervention that wants to bring about change is better seen as a mechanism that gradually resolves/explores uncertainties about system dynamics through learning and adaptation and ongoing sense-making, rather than a series of "fixes" to a well-identified set of problems. This might reveal that a system is a symptom of a larger set of dynamics playing out in the economic system, thereby opening up a wider set of entry points and policy options to "play" with (Meadows 2008; Plsek and Greenhalgh 2001).

These leverage points are neither easily accessible nor are they easy to use if and when we know how to find them. However, this reframing of the policymaking problem is advantageous in the sense that it alters and expands what we seek from it, and not the underlying methodology. The need for simulations and models and for implicit knowledge and explicit expertise remains and indeed is greater than ever before.

Conclusions

This chapter started with two perspectives on the relation between public policy and engineering systems, namely, one, the designers of engineering systems as de facto policymakers and, two, the use of engineering systems methods in the range of tools of public policymakers.

With the growing recognition of the importance of the societal context for engineering systems and the increasing complexity of policy issues, we argue that the engineering systems perspective in policymaking now consists of a layering of methods, where the more formal simulation and data-driven parts have more of the first perspective, while the participatory approaches aim to connect institutional policymakers with the use of engineering systems methods for policy design. The discussions above show that in practice, we see the growing synergies in the last decade even between the two perspectives as modern society needs an amalgamation of both to address the major challenges.

Both public policy and engineering systems recognise that successful interventions into socio-technical systems depend on understanding behaviours of the systems' participants, including their underlying mechanisms of bounded rationalities and societal interdependencies. At the same time, the increasing complexity of policymaking has pushed for a more rigorous, methodological design approach, particularly in more technology-related areas.

Engineering systems as a paradigm has morphed into a practical philosophy for executing decision-oriented interdisciplinary research and development, based predominantly on quantitative models of problems. The more recent enrichment of this paradigm with public policy and other social science aspects makes that the approach increasingly fits fields in which specific problems and goals are difficult to separate from the context and with decentralised planning structures. Public policy, including institutions and officials, need to integrate engineering systems methods into policymaking processes and be amenable to support such analysis with interdisciplinary research.

Within the administrative planning logic, the emergence of a “nonlinear rationality”, bridging technical and communicative approaches to planning, can lead to a dynamic kind of complexity in planning theory that can in turn lead to an understanding of planning premised upon the complexity sciences (Portugali et al. 2012; de Roo and Rauws 2012). While complexity science contributes toward a scientific understanding (in parts) of the dynamism of systems, it is explored and applied in planning mainly through representative instruments such as simulations.

Engineering systems provide a way to move away from preconceived notions of unified and common languages and embrace a pluralistic view of systems. It bridges the classic division between engineers dealing with technical systems and policy and other social sciences.

In an age of long-running crises and increasing complexity, systems continuously navigate the trade-off between robustness and evolvability. In a decentralised planning structure, systems also need to preserve trust. The objective of engineering systems is no longer prediction but an understanding of the essence of the problem that only engineering systems can provide from an elevated and holistic perspective. While this approach might facilitate an intuitive understanding of the problem, more tools and methods are needed to effectively communicate this among actors and more importantly the public. A socio-technical engineering systems perspective can be the ultimate sandbox, embracing a continuous iterative process of incremental improvements guided by a multidomain, multilevel hierarchy of actors with differing levels of agency over the system and by providing open tools and “maps” for guiding decisions in large, complex, and interdisciplinary applications.

Cross-References

- ▶ Designing for Human Behaviour in a Systemic World
- ▶ Engineering Systems in Flux: Designing and Evaluating Interventions in Dynamic Systems
- ▶ Engineering Systems Interventions in Practice: Cases from Healthcare and Transport
- ▶ Ethics and Equity-Centred Perspectives in Engineering Systems Design
- ▶ Evaluating Engineering Systems Interventions
- ▶ Flexibility and Real Options in Engineering Systems Design
- ▶ History of Engineering Systems Design Research and Practice
- ▶ Systems Thinking: Practical Insights on Systems-Led Design in Socio-Technical Engineering Systems

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Transitioning to Sustainable Engineering Systems

34

Chris McMahon and Susan Krumdieck

Contents

Abstract

The industrial exploitation of engineering and technology over recent centuries has had enormous impacts on the Earth's ecosystems, ranging from extraction of non-renewable resources to the deleterious effect of many pollutants. This chapter first reviews such impacts by describing human activities in terms of material flows, the factors that contain them and the principal impacts that they engender, before considering them in the context of recent development of Earth system models of the interlinked physical, chemical, biological and human processes that

C. McMahon (✉)
School of Civil, Aerospace and Mechanical Engineering, University of Bristol, Bristol, UK

Department of Civil and Mechanical Engineering, DTU-Technical University of Denmark, Kongens Lyngby, Denmark
e-mail: chris.mcmahon@bristol.ac.uk

S. Krumdieck
School of Energy, Geoscience, Infrastructure and Society, Islands Centre for Net Zero, Heriot-Watt University, Edinburgh, UK
e-mail: s.krumdieck@hw.ac.uk

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transport and transform materials and energy in complex dynamic ways. The use of modelling of such systems is described, and the engineering approaches to system change to reduce the impact of human activities are outlined, ranging from efficiency improvements, sobriety and substitution through addition of functions for improved control of systems to servitisation and to the various approaches of the circular economy. Transition engineering is introduced as a systematic approach to the embedding of sustainability thinking into engineering practice. The chapter concludes with a discussion of the key questions faced by those seeking to effect sustainable transitions and of the challenges faced by engineering systems designers arising from the need for such transitions.

Keywords

Engineering systems · Engineering systems design · Earth system · Climate · Material flows · Sustainability transitions · Transition engineering

Introduction

The UN Conference of the Parties COP1 Berlin Climate Summit in 1995 was convened to address high rates of CO_2 and other greenhouse gas emissions. In that year, the global fossil fuel production added six gigatons of CO_2 to the atmosphere. In 2018, 3 years after UN COP21 reached agreement to limit global warming to well below 2 °C, the fossil fuel consumption added ten gigatons of CO_2 to the atmosphere. The scientific consensus is that continued 'business-as-usual' production of fossil fuels risks pushing the accumulated CO_2 beyond the 2 °C failure limit by 2030. All of the fossil fuel production, transport, refining, distribution and end uses are engineered systems. The UN Intergovernmental Panel on Climate Change (IPCC) scientific review has clearly spelled out the failure modes of the fossil fuel systems. Transition engineering of unsustainable fossil fuel systems is the most comprehensive, most time-critical mission engineering professionals have ever undertaken. This chapter explores the emergence and massification of the discipline to accomplish this unprecedented undertaking.

Industrial application of the engineering and technology enterprise across the world over the past 70 years has had enormous impacts on all of the ecosystems across planet Earth throughout the material cycle from extraction of non-renewable resources and exploitation of biocapacity resources to the effects of pollution and waste, agriculture and land use conversion. The extent of human activities is such that they have become geologically significant in their effects giving rise to the use by some of the term 'Anthropocene' to describe the current epoch (Crutzen 2006).

Scientific consensus about the nature and scale of the impacts of the industrial fossil fuel enterprise has been clear for decades. However, the scientific warnings about the harm that must stop have not resulted in appreciable change in engineering education or professional practice. Political rhetoric has been dominated by declaring emissions targets to be achieved decades in the future, and encouraging growth in renewable energy development and consumption of products deemed to be 'green'. Eminent climate scientist James Hansen called for leaving fossil carbon in the ground through setting production quotas and carbon taxes, and rapidly increasing nuclear power generation (Hansen 2009). Popular media has seen increased discussion of adopting ‘circular economy’ principles emphasising reuse, remanufacture and recycling, and greater emphasis on services and green consumer behaviours. These types of changes are seen as counter to continuing the historical progress of economic growth. Improved control of engineering artefacts and processes, new energy storage systems and new applications of data science and computational intelligence would be required to adapt to the irregularity of renewable energy availability. The 2021 International Energy Agency (IEA) scenario abruptly reversed the decades of forecasting fossil fuel demand growth and called for ceasing new fossil fuel extraction immediately and halving of fossil fuel production by 2050 (IEA 2021). Recently, shareholder decisions at Shell and ExxonMobile that require the companies to address risks of climate change to their profitability, and the development of impact investment funds, have added financial impetus to the growing political and scientific pressures for action on emissions. But unresolved problems of how to achieve decarbonised power production, transport and heating remain.

As the Earth warming races toward 1.5 °C, the impacts of unprecedented weather events are so grave that counter-industrial and de-growth ideas are gaining prominence (Malm 2021). These ideas see the need for severe constraints on luxury travel and consumption, plus multi-facetted radical changes in lifestyles with an emphasis on sobriety and frugality, combined with a reduction in the complexity of engineering systems and even a deliberate adoption of simpler technologies (Bihouix 2014). Counter-industrial adherents see end-use de-growth and simplification as the direct means to reduce fossil fuel consumption, but the ideas have virtually no political or economic support (Buch-Hansen 2018). These attitudes represent points on a wide spectrum of opinion and there are many others in varying combinations (Dusch et al. 2010), such that there is little agreement on how to proceed, and little political enthusiasm for responding to any but the most optimistic viewpoints.

In this context of dire scientific warnings, political declarations, social concern and very limited substantive change to date, what is the role of engineering systems design? The engineered artefacts that we use today, our buildings and communities, our energy, manufacturing and transportation systems, and other aspects of the built environment have been designed and made at a time of ready availability of fuels and materials, in an economic system that values growth above all other factors. The present state of the world is a function of these historic paths taken – we are in a ‘path-dependent’ position (Barnett et al. 2015). While there is a lot of public discourse today about the need to radically alter our economic systems, discourse and declarations so far have not been sufficient to generate engineering transitions from the un-sustainable path of fossil fuel production growth. If change to economic systems is not possible socially or politically, how then might less damaging approaches be identified and adopted? There is surely an important role for the engineering systems designer here, to explore and evaluate alternative systems approaches, innovate energy transitions that downshift fossil carbon production and consumption, and to advise politicians and other decision-makers on the engineering implications of policies.

This chapter first reviews scientific findings to develop required constraints on material development, noting that fossil CO_2 and other greenhouse gases are only one of a number of constraints required to downshift un-sustainable aspects of industrial economies. It will then review current thinking on these constraints from a systems perspective before considering approaches to the modelling of such systems that can inform our professional engineering practice. In the final two sections, engineering approaches to systems change will be introduced and then critically examined, introducing the notion of transition engineering as an approach for engineers in all sectors to change the existing systems they are knowledgeable about in ways that they know will work, with down-shifted energy and material use. It will be emphasised that Engineering Systems Design offers approaches that give engineers insights into those systems and how they operate to achieve the tens of thousands of transition projects around the world.

Energy and Material Production and Consumption

The production, operation, maintenance and disposal of engineered products and systems, and of the products of their consumption and use, may be seen in terms of the processing and flow of materials and energy. Industrial production and consumption are based on the use of use of energy and also of all manner of materials, whose extraction and production are in turn enabled by the use of energy. The production of materials and of the artefacts for which they are used leads to wastes and environmental impacts such as spoil heaps from mining and emissions of particulate matter, toxic chemicals and the like. The disposal of products at the end of life leads to further wastes. All these are impacts on the natural environment, and the whole process can be thought of in terms of stocks and flows of materials and energy (Haas et al. 2015).

Material flows start with the harvesting of renewable resources and the mining/extraction of non-renewable resources, which then become part of the *forward logistics* resource supply system. These resources are transformed by manufacturing systems to become goods for final consumption or use. All forward logistics processes consume energy (itself from renewable or non-renewable sources) and consumption generates wastes that enter a *reverse logistics* cycle. What can be *re-used, remanufactured* or *recycled* will re-enter the resource supply cycle while what remains will be put into a ‘sink’, such as a landfill but also the ocean, the atmosphere or other terrestrial means of dispersion. Expressed in these simple terms the challenges of sustainable development, from an engineering point of view, concern the sustainability of the resource use and of the use of sinks. In particular, what are the implications of the rate of use of renewable and non-renewable materials and energy that are supporting the human population and its economic activities, and what are the impacts of the resulting flows to sinks? More specifically, the engineering challenge involves making as efficient a use as possible of materials and energy, minimising the use of non-renewable resources and flows of materials to sinks, and minimising the impact of the flows that still remain (e.g. to stop uncontrolled flows to the oceans or the atmosphere, or to convert undesirable flows into more benign flows) (Ellen MacArthur Foundation 2013).

At the ‘source’ end of the material flows, there are three key interlinked issues that impact the rate at which materials may be exploited:

1. The available *reserves* of material.
2. The rate at which the material can be economically extracted, transported to its point of use and processed into a useful form (e.g. conversion of biomass into biodiesel or the conversion of crude oil into gasoline). The processing may take place before, during or at the end of the transportation process depending on where the material is extracted, where it needs to be used and the complexity of the conversion/refinement process.
3. The energy and other resources that need to be expended in the extraction, transport and refinement of the material.

Factors that Constrain Industrial Material Development

The available reserves of material depend on the rate at which it can be economically extracted. The supply of the material in the market depends on the extraction rate plus the recovery and recycle rate. As an example, consider the metal copper. It is a relatively common element in the earth’s crust, with an average concentration of 0.005–0.007%. If all of this was extractable it would provide a nearly inexhaustible supply. However, only much higher density deposits (e.g. 0.2–0.5%) close to the surface are currently economically extractable, and at current rates of mining of approaching 20 million tonnes per year this is in the order of 50 years’ supply, although undiscovered deposits in the upper part of the earth’s crust are estimated to have about four times this quantity (Wikipedia Peak Copper 2014).

The *rate* of supply that will be possible in the future is, at least in the short term, more important than the total supply, and this is a significant source of argument. For many years there have been concerns about the continued availability of copper for example, but in practice the estimated reserves have continued to increase for many years. But there is a hypothetical point in time, as copper becomes more difficult and expensive to extract, when the rate of extraction will peak and thereafter supplies will diminish (even though there will still be very significant reserves). This is known as *peak copper*, and it has been argued in recent years that we are quite close to this point in time. A counter-argument is that as technological developments occur in prospecting, mining and the processing of ores, less rich deposits will become more feasible to work, so extending the effective reserves and moving the date of peak copper into the future. There are three important points to make in this regard: firstly, this argument is valid when energy is readily available for extraction and refining, but energy constraints may bring forward the peak date; secondly, there will ultimately be limits in the available investment capital to invest in the technological developments and, thirdly, copper is widely recycled (and in 2018 this provided 30% of worldwide copper supplies (Loibl and Espinoza 2021)). Clearly, resource availability constraints may be ameliorated by improved rates of recycling and re-use, and as materials get more expensive they can also be substituted e.g. aluminium for copper in electrical conductors.

Resource supply constraints apply to many different materials, but most importantly in fossil materials used in energy supplies where these same ideas of peak supply are found. In the 1950s American geologist M King Hubbert presented models for the productivity of oilfields and based on a development of his ideas it has been argued that the world supply of conventionally drilled oil peaked in the early years of the twenty-first century, although overall supply of liquid fuels has been maintained through the extraction of oil by hydraulic fracturing and other non-conventional means (Hubbert 1956).

Impact Categories of Industrial Material Development

At the other end of the material flows there are sustainability constraints concerning the ability of the natural environment to absorb materials in sinks. This is seen in many different ways – for instance the physical space limitation from the need to find landfill sites for discarded materials, or the degradation of aquatic environments by unmanaged plastic waste. The major environmental impact categories of human activities are considered to be (Bisin and Hyndman 1992):

- Acidification: of soils and waters through the transformation of air pollutants such as sulphur dioxide and nitrogen oxide into acids.
- Eutrophication: enrichment of water by inorganic plant nutrients e.g. from fertilizer runoff leading to algal blooms.
- Ozone depletion: breakdown of ozone (O3) in the upper atmosphere through the action of long-lived chlorine and bromine compounds, methane (CH4), nitrous oxide (N2O), and water vapour H2O.
- Photochemical ozone creation: tropospheric or ground-level ozone formed under the influence of sunlight when oxides of nitrogen are present.
- Global warming: changes in the ability of the atmosphere to absorb infra-red radiation through variation in the quantities of CO2, methane, oxides of nitrogen and other materials.
- Dispersion of plastics and other man-made materials in the environment, aggravated by the slow rate of degradation of such materials

There are also various effects on life on the planet, including human life, from man-made material toxicity. Engineers have a very significant role in causing all of these impacts, especially through the products of combustion of fuels, but also through wastes from production processes, through the effects of packaging, man-made chemicals and drugs. Since the beginning of the industrial revolution, unintended consequences of successful engineered systems have been identified by scientific observation, and corrective measures have been developed by engineers. These measures have then been legislated through regulations and limits on air and water pollution and health and environmental impacts. Tetramethyl lead gasoline additive and sulphur dioxide stack emissions from coal power plants are historical examples of successful engineered systems, scientifically documented harm, technology development to downshift the unsustainable aspects, and finally regulated constraints on the engineering design.

Engineering Systems in the Earth System

As has also been described earlier in the Handbook on sustainable futures from an engineering systems perspective, the engineering activities described above may be considered in terms of a number of engineering systems – for example for manufacturing, transportation, energy and communications – through which there is a flow of materials and energy to meet human needs. These engineering systems can in turn be thought of as interacting with the Earth's natural systems including the atmosphere, cryosphere, land, ocean and lithosphere. The whole operates as a 'system of systems', described by the Institute of Geophysics and Planetary Physics (IGPP) at UCLA using the term 'Earth system' - a suite of interlinked physical, chemical, biological and human processes that cycle (transport and transform) materials and energy in complex dynamic ways (Steffen et al. 2004). This is the subject of the recently developed discipline of Earth System Science (ESS), a multidisciplinary undertaking aimed at understanding the structure and functioning of the Earth as a complex adaptive system. Steffen et al. (2020) suggests that "the grand challenge for ESS is to achieve a deep integration of biophysical processes and human dynamics to build a truly unified understanding of the Earth system", and it is this understanding that will guide the trajectories in which engineered systems should develop.

Earth systems sciences developed rapidly in the latter half of the twentieth century, driven by new methods of gathering data about the state of the Earth, especially Earth observation from space, the use of ice core data to study atmospheric and climactic changes and a plethora of other physical measurements. Key concepts that were developed include (Steffen et al. 2020):

- The notion of dynamic, co-evolutionary relationships between elements of the Earth system
- The possibility of non-linear changes including tipping points and feedback loops as a consequence of these relationships
- The notion that climate change, biodiversity loss, pollution and other environmental issues are linked to human activities especially high consumption and urbanisation to the extent that a new geological era – the **Anthropocene** – may be discerned,
- A framework of **planetary boundaries** – suggested limits to the biophysical carrying capacity of the Earth, related to human activities and their governance, and guiding the levels of human-driven perturbation that can be absorbed.

A leading contributor to the development of Earth systems sciences has been NASA, through its Earth Observation programme. NASA scientists were instrumental in the construction of the 'Bretherton diagram', a conceptual map of Earth system processes, an extended version of which, fully integrating a representation of human interaction with the Earth, is shown in Fig. 1 (Steffen et al. 2020). The 'energy systems' and 'production and consumption' elements of this diagram are extensively composed of technical, engineered systems, and these also support or contribute to the information/material fluxes shown in this diagram.

The approaches that we have read of in this Handbook may be used to examine the socio-technical engineering systems within the Earth system in more detail, including consideration of the physical artefacts which they comprise, the technologies on which they are based, their operation and embedding in human social and political systems. Of particular importance to understand are the possibilities for technological change and the response of these systems to shifting pressures within the social and economic landscape. Over the past century we see especially:

1. The evolution from individual artefacts to the highly interlinked systems of systems described by de Weck et al. (2011).
2. A rapid increase in the physical numbers of artefacts and the size and scale of built infrastructure. This all has implications for energy and materials consumption, as for example new roads encourage more traffic and require energy and materials to be expended in their maintenance.
3. Increase in the complexity of artefacts, as noted by Arthur (1993) "functions and modifications are added to a system to break through limitations, handle exceptional circumstances or adapt to a world itself more complex". This may be seen,

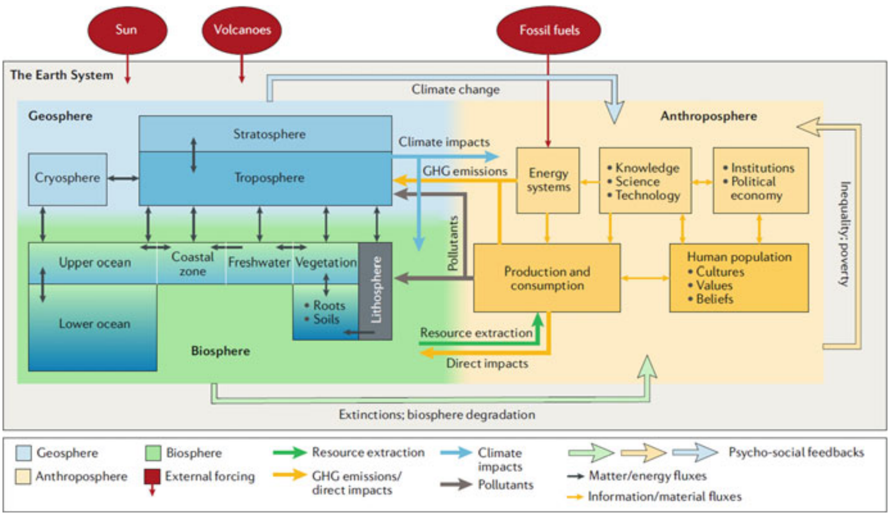

Fig. 1 An updated Bretherton conceptual model of the Earth system. (Figure reproduced from Steffen et al. 2020)

for example, in examples ranging from the addition of emissions reduction devices or control systems to engines, to the increase in bureaucracy in organisations.

4. The impact of technological innovation, and its interrelationship with economic development and pressures.

These developments contribute to drivers for changes in material and energy consumption that compound the expansion already seen from increases in population and economic activity. The first driver is the increased energy consumption and material use arising from utilisation of the outcomes of historical manufacture of artefacts and building of infrastructure noted in point (2) – in fact it has been argued that this relationship is such that current energy use is directly correlated with the historical time integral of past world economic production (Garrett et al. 2020). The second is the energetic and material costs of the complexity described by Arthur, especially the use of the extended range of materials such as rare earths and precious metals, driven by electrification of energy supplies and the digitisation of systems, such that the European Union has uses the term critical raw materials (CRM) for those raw materials (currently 27 materials) that are economically and strategically important for the European economy but have a high-risk associated with their supply (European Commission 2017). The impact of these developments is illustrated by the manufacturing complexity and supply chain extent needed to manufacture a modern car or aircraft compared with their historical ancestors.

These compounding factors multiply the challenges faced by the need to decarbonise to reduce the impact of climate change or to find alternative energy sources to counter the diminishing supplies of fossil fuels, which pose formidable issues to overcome. Indeed, it is argued by some that decline has been forced on historic civilisations by material and energy limitations broached by increases in societal complexity and that modern civilisations may face the same issues (Tainter 1988). The question becomes whether it is possible to identify sociotechnical pathways that permit a transition to a more sustainable Earth system, and what pathways and in what combination offer the best approach within political and sociotechnical constraints. Geels and Schot (2007) identify four types of pathway in this respect:

- **Transformation** pathway: Modification of the direction of development paths and innovation activities in response to pressures for disruptive change in the absence of sufficiently developed niche innovations.
- **De-alignment and re-alignment** pathway: Opportunity for emergence of a dominant niche-innovation from the emergence of multiple competing innovations in response to emergence of large and sudden problems with no immediately available niche innovation.
- **Technological substitution** pathway: Where pressure for disruptive change may be addressed by the breakthrough of sufficiently developed niche innovations.
- **Reconfiguration** pathway: Triggering of adjustments in basic architecture of systems by initial adoption of symbiotic innovations to solve local problems.

	Ecocentrism		Technocentrism	
	Deep ecology	**Communalism**	**Accommodation**	**Cornucopian**
Green labels	Extreme **preservationist**	Resource **preservationist**	Resource **conservationist** and managerial	Resource **exploitative** and growth oriented
Type of economy	**Very deep green economy**. Highly regulated	**Deep green economy**. Steady state economy	**Green economy,** green markets, economic incentives	**Anti-green** economy. Unfettered free markets
Management	**Reduced** scale of economy and population.	**Zero** economic and population growth.	**Modified** economic growth.	**Primary** policy to maximise growth.

Fig. 2 Examples of stances taken towards sustainability. (Simplified from Dusch et al. 2010; Pearce 1993)

We suggest that a key challenge that we face is that there are advocates for each of these pathways, but there is no agreement about the likely success of any of them, and in the meantime political and economic pressures encourage continuation on the trajectories that we know to be unsustainable. In the words of Funtowicz and Ravetz (1993), in a world of post-normal science "facts [are] uncertain, values in dispute, stakes high and decisions urgent". For some, technological substitution, especially of renewable energies and electrification, offers a way forward; for others, material considerations will constrain such developments, and fundamental changes in economic systems (e.g. 'degrowth') are required. The 'values in dispute' lead to a range of stances being taken, as shown for example in Fig. 2. What should be the role of engineering systems design in this 'post-normal' world and what light may it shed on the key questions?

Approaches to System Change

An understanding of the state of the Earth system, and of possible pathways for change, must come from models that give us insights into these, and in this regard a number of modelling approaches have been developed to model at all levels from the behaviour and impacts of individual artefacts through to those of the whole system. At the highest level, Earth system models (Flato 2011) model the various elements of the Earth system in Fig. 1 and their interactions. In recent years these have concentrated especially on modelling the interaction of biogeochemical processes with the physical climate, exploring the effect of emissions resulting from human activity, but planetary boundary issues such as ocean acidification, ozone depletion and land system change are also extensively modelled (Lade et al. 2020; Nash et al. 2017). Considering resource extraction, detailed modelling of supply and reserves is carried out for resources from oil through metals and minerals to fish, timber and other biomass (Sorrell et al. 2010; Vidal et al. 2017; Ovando et al. 2016; Sharma et al. 2013).

Such high level models do little to guide detailed engineering decisions in the design of technical/engineered systems, and for that purpose a variety of other approaches may be used, from eco-design methods that embed distilled heuristics on environmental impacts (Knight and Jenkins 2009) through various design-for-X techniques that facilitate the repair, recycling and remanufacturing of manufactured artefacts (Sassanelli et al. 2020) to life cycle analysis (LCA) tools that enable a variety of life cycle impacts to be modelled at different levels of fidelity and granularity (Finnveden et al. 2009). Great strides have been made in the use of LCA for design support, but achieving a thorough understanding of impacts is still challenging, owing to the difficulty of modelling all of the life cycle of artefacts, and the need to have extensive and detailed information about the artefact. These factors arguably make LCA difficult to apply in early design stages when important decisions are made.

LCA and the other design support tools also struggle to provide a basis for understanding the consequences of system interactions, such as the impacts of user behaviour and the effects of carrying out engineering activity at scale. In the 'rebound effect', for example, technological improvements to increase the efficiency of energy and other material use may have a lower-than-expected beneficial impact on consumption because the improvements may allow economic activity that would otherwise not have been possible and/or because the savings that accrue may be spent on activities of similar impact (Berkhout et al. 2000). To understand such cases, and especially to arrive at insights into high-level interactions, system dynamic modelling (SDM) may be used (Sterman 2000). SDM considers complex systems in terms of stocks and flows, relationships, feedback and reinforcing loops, and was the modelling approach used in the celebrated Limits to Growth study of the Club of Rome (Meadows et al. 1972) that considered the systems implications of continued human population growth and attendant industrial and food production on an Earth constrained by availability of resources and ability to handle pollution. Today, system dynamic modelling is seeing widespread use to generate insights into the likely dynamics of the impacts of human activity on the environment. Examples include the sustainability of materials supplies (Sverdrup et al. 2019), waste management (Kollikkathara et al. 2010), the rebound effect (Freeman et al. 2016) and the management of land systems (Robinson et al. 2018) among many others.

Another tool that may be useful in informing system choices that are made is the use of energy return on energy invested (EROEI) as a measure (Murphy and Hall 2011). EROEI is defined as the energy returned to society using some energy source divided by the energy expended throughout the lifecycle in accessing that energy – for example in prospecting, drilling, transporting and processing of oil – and is a measure of the difficulty of obtaining an energy resource. Historically, EROEI for conventional oil supply has been calculated in the range 30 to over 100, whereas that for biofuels can be very low (in low single figures) as can that for solar panels in some locations with low levels of solar irradiation. Rye and Jackson (2018) present an interesting use of EROEI and SDM together to evaluate different energy-transition models. EROEI may be especially useful in guiding the choice of which renewable energy systems to adopt.

Engineering Approaches

Although there is considerable dispute about the full extent of the measures that should be taken, especially about the possibilities for effecting change within the constraints of existing socio-economic systems, at a high-level the engineering change requirements are clear: accomplish a rapid reduction in carbon-based fuels (both owing to their contribution to climate change and the likelihood of supply constraints). Additionally, the new engineered systems will fit within the constraints for sustainable non-renewable and renewable resource use, land use and pollutants. In this regard a number of engineering approaches to system change are used (Arthur 2009).

The first step that is often attempted is to improve the efficiency of operation of an artefact without changing the solution principle embodied in the designed artefacts. Buildings are made more energy efficient by increasing insulation. Motor vehicles are made more fuel efficient by reducing their size and weight and by improved streamlining. Optimisation is used to reduce component weight. But, in general, such approaches do not address fundamental issues with the solution principle: a gasoline engine car may be improved by reducing its drag, but it remains that it is a generator of greenhouse gases. A building may be retrofitted to reduce use of heating fuel, but still be situated where only commuting by private car gives access to the building. And these types of energy management changes do not address the issues of carbon in the upstream supply chain, or to the issues of financing such energy efficiency improvements. In recent years, there have been developments in approaching the work of systems change using different perspectives.

Substitution

Perhaps the most common approach to apply to eliminate an issue is substitution (called internal replacement by Arthur (2009)). Alternative materials are substituted for those in short supply or whose use is problematic, such as asbestos in brake linings or Chlorofluorocarbons (CFCs) in air conditioning systems. In the drive to decarbonise, electric motors are substituted for internal combustion engines, heat pumps for gas boilers, batteries for fuel tanks. In cases where batteries offer insufficient energy density, biofuels may be used in place of fossil fuels. Substitution is also used for performance improvement: carbon-fibre composite materials allow aircraft weight to be reduced and thus fuel economy improved. More sophisticated alloys allow weight reduction in automobiles. Improved insulating materials reduce heat loss.

Substitution can be used at all levels in a system from coatings on a part through sub-systems to whole system change. In regard to the latter, electronic video communication may be used as a substitute for business travel to meetings, as was widely done in the COVID-19 pandemic. Electrified trams, metro or light railway systems may substitute for automobiles, wind turbines and solar farms for coal-fired power stations.

In addition to substitution, adding functionality to artefacts is a widely used strategy to improve efficiency of operation or to eliminate undesirable effects.

Arthur (2009) calls this 'structural deepening' because it extends the function structure of the artefact. As examples, emissions control equipment may be added to engines and combustion systems to reduce emission of harmful gases or particulates, and addition of carbon capture and storage capabilities to energy generation and industrial process plant would also come into this category. Control systems may be added to heating or air conditioning systems to improve their efficiency of operation. Sensors may be used to try to improve traffic flow in cities, or to improve the operation of all sorts of plant from water and sewage treatment to chemical plant (Mehmood et al. 2020). A great deal of the current move towards 'smart' systems and the 'Internet of Things' falls into this approach of functional extension.

A recent concept is substitution of *not* carrying out an activity or *not* using a product as a means of reducing carbon and ecological footprint. The ability to reduce energy use while maintaining wellbeing and essential activities is termed 'adaptive capacity'. In 2020, the Covid 19 pandemic required restrictions on travel for non-essential purposes, and subsequent 'dread' behaviour change demonstrated the existence of adaptive capacity for cycling and the rapid development of adaptive capacity for not travelling for business by substituting virtual meetings, teaching and medical and other services (Watcharasukarn et al. 2012). By far the largest Covid-19 energy reduction was in aviation (Sung and Monschauer 2020).

Circular Economy, Repair, Recycling, Remanufacturing

While the use of fossil fuels implies an inexorable one-way flow from their extraction from the Earth to dispersion of combustion products into the biosphere, that is not necessarily the case for material resources. Metals, glasses and many polymers may, at least in principle, be collected, sorted, processed and reused or repurposed, reducing the rate at which virgin materials need to be extracted and processed, and reducing the impact of waste materials on the biosphere. Artefacts such as vehicles and their parts may be repaired, refurbished or remanufactured to extend their useful lives and in that way reduce material resource requirements (Ijomah et al. 2007). Containers such as glass bottles may be cleaned and reused. Judicious maintenance and repair of buildings may allow them to be used over decades or even centuries.

In most cases however, materials are so mixed up and contaminated at the end of life that it is not possible to recycle them into identical uses. In such cases materials may have a 'second life' in a less demanding role than the first use – sophisticated steel alloys may for example be mixed together with other materials and end up used for an application such as reinforcing bars in concrete. We see such 'downcycling' with whole artefacts also: a traction battery from an electric car may, after its performance has degraded through use, have a second life for some time in household electrical storage (Jiao and Evans 2016).

In addition to materials, a good deal of energy is often used in the manufacture of products, and this energy is regarded as embodied in the artefact. For many products – consider an electric drill, for example – the embodied energy is a significant part of the energy used throughout the life of the artefact. In such cases, using the artefact more extensively, for example by using it in a product-service system (PSS), or achieving multiple uses through sharing may spread the embodied energy over more uses, allowing fewer devices to provide the same end effects for the users (Matzler et al. 2015).

Downcycling, recycling, sharing, repair, remanufacturing and reuse are all processes with the circular economy, an economic system that seeks to replace the linear flow of materials from 'source' to 'sink' to a circular process in which materials, products, constructed artefacts and systems are kept in use for longer, improving the productivity of you of the resources. The circular economy concept has not had rigorous engineering analysis of the input-output energy and material flows for the whole systems, which would include significant transport energy in gathering up end of life artefacts, sorting, deconstructing and re-processing. In particular, the costs and benefits of substituting upstream artefact and packaging design for zero waste, reduced throughput through longer life, and recyclability may be much more advantageous than adding waste processing to existing artefact designs and volumes (Korhonen et al. 2018).

Products, Services and Product-Service Systems

As mentioned earlier in the Handbook, at the level of an economic system, another approach to substitution is to increase the emphasis on services in the economy, on the basis that the delivery of services may be less energy and resource intensive than the manufacture and use of physical artefacts, and thus economic activity may be decoupled from use of polluting resources (Lightfoot et al. 2013). Delivering transportation as a service may be less resource intensive than individual ownership and use of vehicles. Laundry services may be less resource intensive than households using their own washing machines. Furthermore, in many business cases, delivery of a service is combined with manufacture and/or support of a physical artefact in PSS, as in the examples of 'power by the hour' supply of gas turbine engines, or through-life support of buildings. The notion is that through such modes of operation, companies are incentivised to make their products more resource efficient, easier to repair and so on.

Transition Engineering

The term 'transition' is used for the process of moving from environmentally damaging levels of pollution or resource use to the required constrained levels, especially in the context of transition projects that downshift production and use of fossil fuels. Communities called 'transition towns' first developed the impetus for downshift of dependence on fossil fuels as a way to manage the local risk to global issues (Hopkins et al. 2008). Transition town groups procure education about the issues of peak oil and global warming, and they work on specific projects to build local resilience through developing local food networks, farmer's markets, permaculture, recycling, community energy and other largely non-engineering endeavours. Recent studies have indicated that lower carbon lifestyles and sensibilities are correlated with higher wellbeing and satisfaction, so engineering lower consumption transformations can be seen as responsible for both environmental and social benefits (Vita et al. 2020).

The term transition engineering describes the engineering discipline that embeds sustainability thinking into engineering practice by focusing on changing those aspects of existing systems that are unsustainable. Transition engineering is a ‘corrective’ engineering approach, following the historical developments of safety engineering, emergency management engineering, and waste management, for example, that also developed after untenable and disastrous failures of economically successful and politically acceptable engineered systems. Safety engineering emerged after 62 mechanical industrial engineers met in response to the Triangle Shirtwaist Factory disaster in 1911 where 148 young women were killed. The group wrote up their agreed charter, and then went back to their factories, changed the doors so that workers could escape in the event of a fire, and changed the future. The Safety Engineering tenets include to “prevent what is preventable”, to “be honest with employers and the public about the nature of the problems and of possible solutions, and to “work on the systems in which you have expertise”. Within just a few years, the work of Safety Engineers was so successful that worker deaths and injuries in many industries dropped dramatically, industry was paying for training and research and insurance companies were requiring Safety Engineering training and measures. It was not until 60 years after the formation of the American Society of Safety Engineers that the US government established the Occupational Health and Safety Authority. And it was 90 years later when an economic study revealed that for every dollar spent on preventing accidents, six dollars of benefit were returned to the society. Transition Engineering uses the model of Safety Engineering to take the approach of working directly on down-shifting of technologies, activities, and operations of systems that are not sustainable.

The preliminary groundwork for Transition Engineering is to frame up the project work in terms of a specific, local, identifiable engineered system. This is a “ground-up” perspective which is in contrast to the historical “top-down” approach of seeking to develop energy supply substitutions or to manufacture more sustainable products without substantively changing the economics or consumer behaviour. The project must then identify the essential or important good or service provided by the system. Engineering projects always have purpose and performance objectives, but for transition the question of how or whether the engineered system provides essential needs for wellbeing or regeneration of the environment can be challenging to answer. If the system provides only luxury or optional services, then the operation can be curtailed or converted to an essential need. If the system does meet essential needs, then there are already known changes that can be made, or changing the system to downshift fossil carbon may be a ‘wicked problem’ (Rittel and Weber 1973). A wicked problem is characterised by the following aspects:

- The current system meets current standards and cost targets and provides for an essential need.
- The current system is un-sustainable because it is drawing down finite biocapacity, materials, social capacity, equitable access to essential goods or services, or autonomy.
- The current system meets the needs and provides profits for some people.

- The current system causes pollution, harm, loss of dignity, or other loss of social value.
- The current system cannot continue and must change.
- The current system is entrenched and cannot be changed.

The transition engineering method has been developed for multidisciplinary stakeholder groups to find confident next steps by innovating change projects in existing systems that pose wicked problems. Wicked problems once unpacked according to the factors above can be seen to not have readily available solutions, more often than not because the means of carrying out changes are not known. The transition engineering process is called interdisciplinary transition, innovation, management and engineering (InTIME). The method involves seven steps to help engineers develop projects to deal with changing unsustainable activities, broadly as follows and as shown in Fig. 3 (Krumdieck 2019):

1. Understand the historical, social, cultural and political context, the change dynamics of the past that have led to the present situation. How were the same essential needs met in the same place as the current wicked problem? Did people in 1911 have the same wicked problem? What factors were in play when historic choices were made?
2. Assess the present situation, including current capabilities, investments, assets and liabilities, and auditing energy use and user behaviour. Gather relevant data and explore different representations of the data in different ways with stakeholders. Examine the current values and assumptions of the different stakeholders.
3. Create future scenarios to get a consensus view of both inertial trajectories of current trends, and limitations of carrying capacity and resource scarcity. Crash-test any policies or plans that are in play with simple models to interrogate

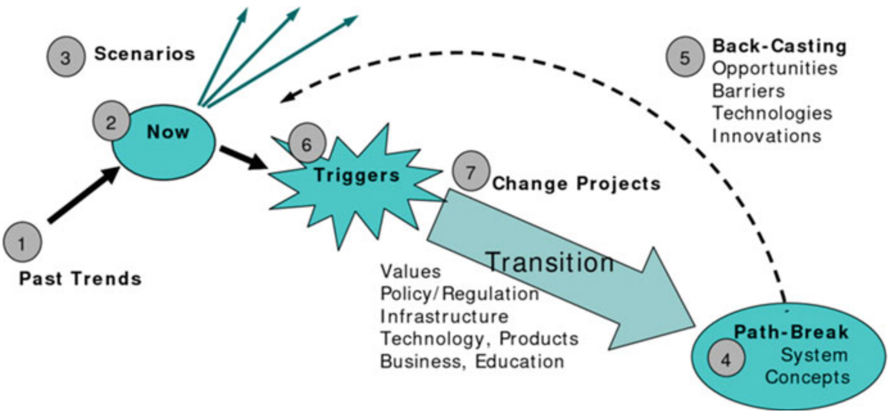

Fig. 3 The seven steps in the InTIME approach for addressing wicked problems of complex systems (Krumdieck 2019)

whether they meet the hard constraints of downshift in fossil carbon or other unsustainable activities as expected trends develop into the near future. For example, a policy to support purchase of electric vehicles can easily be crash-tested to assess the cumulative carbon emissions into the future under different scenarios of fleet mix, mileage, and electricity supply. Scenarios and assumptions that do not pass the crash-test are then communicated as non-starters and are discarded for future consideration. The forward operating environment envelope is formed by the hard constraints to downshift unsustainability according to science and targets. For example, staying below the global warming failure limit of 2 °C requires downshift of fossil carbon extraction of 80% by 2040.

4. Explore path break concepts that set aside current assumptions about behaviour and economics to consider the forward operating environment beyond the end-point of the time-frame of the current engineered system. The fourth step involves "visiting" the year 2121 in the specific location of the study, and "exploring" how they meet the specific essential needs without fossil fuels and with only realistic and workable concepts backed up with strategic analysis of complex systems and energy analysis.
5. Analyse the path break concepts discovered in 2121 by backcasting, to see how they differ from the current situation and to analyse the barriers and strategies to change existing systems. What can the people of 2121 do that we can't do today? What would start now that would lead to that capability being available in the near future?
6. Create the insight and innovation space. Identify trigger events that, if applied at the right time, enable a great amount of change to be possible. The challenge is to communicate the advantages and benefits of adaptive change, and to initiate a disruptive event that enables an organization to get out of the rut and get unstuck from the current wicked problem.
7. Develop a plan for at least one shift project. The shift project plan will achieve downshift in fossil carbon supply and demand, realised to make best use of the current available resources. Through these projects, society will be more resilient to peak oil and climate change events. Shift projects will fit within the hard constraints, and will generate real value in regeneration of biocapacity, social capacity, equity of access to essential needs and autonomy for all of the stakeholders.

Discussion

The pressing nature of the environmental challenges that we face is such that it is incumbent on all engineers to strive to design, manufacture and operate products and systems that are less damaging. The previous section has indicated some of the approaches that may be used to address this task. But it is also important for the engineering community as a whole to reflect on the impacts of the totality of engineering activities, and to consider at a whole systems level what are the most appropriate pathways to take. Just as Earth System scientists study the geophysical processes that lead to planetary boundaries and advise on the impact on these, so should Engineering Systems designers study the implications of engineering systems choices at all scales from individual artefacts to Earth System and advise on impacts and choices. In this regard it is imperative that we understand what are the implications of engineering systems design choices when implemented at scale: what will a planetary transition away from fossil fuels mean in terms of resource requirements for the substitute technologies? What are the likely consequences of continuing to increase the complexity of engineered systems, especially through use of devices using critical raw materials? Is a widespread substitution of bio-derived materials – for plastics, chemicals and fuels likely to be feasible at scale? What are the prospects for carbon capture technologies or for nuclear fusion? This section will attempt to summarise some of the arguments that may be found in these areas and will make a plea for the search for answers to be a central focus of the engineering systems design community in the coming years.

Perhaps the central question of our times, as we lead into the 26th UN Climate Change Conference of the Parties (COP26), is whether it will be possible to transition way from fossil fuels to renewable sources at the rate required to avoid dangerous, irreversible climate change. There are robust arguments for the case that solar, wind, wave, hydro and other renewable sources, in combination with massive demand reduction, can meet the needs of transition, for example claiming that these can supply 80% of needs by 2030 and 100% by 2050, with no impact on economic growth (Jacobson et al. 2017). Many countries throughout the world have made commitments to using electricity in place of fossil-fuel-burning devices – electric cars and heat pumps for space heating for example (HM Government 2020). However, other voices call for caution, citing the low energy density of many renewable sources (Smil 2016), the extensive specialist raw material requirements for batteries and electrical equipment (and concrete, steel and composites for wind turbines) (National History Museum 2019) and noting that despite progress in rolling out renewable energies, demand for fossil fuels continues to rise.

A particularly important question for engineering systems designers is the level of system complexity that can be supported within resource and pollution constraints, and in this regard an understanding of trade-offs is very important. Control systems and smart devices allow improvements in system performance, especially reductions in fuel use, but require electronic devices produced by a very energy-intensive supply chain with a voracious appetite for critical raw materials for which recycling rates are close to zero. If materials become less accessible, and we need to reduce energy usage in their mining and processing, will it become impossible to sustain that level of complexity? Or will we be able to design devices which can be repeatedly reused in different applications? Even with more efficient and effective use of technologies, where are the limits? The original Limits to Growth study considered the use of more effective pollution control technologies and reductions in the amount of non-renewable resources needed per unit of industrial output. While these would allow prosperity to be maintained for an extended period they would not prevent an eventual decline owing to the accumulated resource costs of the technologies (Meadows et al. 1972).

The highly dispersive use of miniaturised devices is also an issue for the circular economy, as is the dispersive use of materials such as titanium and cobalt in paints and pigments, and the recycling challenges posed by high-performance materials such as composite materials and micro-alloyed steels. There is also a significant energy cost in the reverse logistics, cleaning and reprocessing of products and their materials. Some of these issues may be addressed at least in part by design changes, but the trade-offs between artefact performance in use (for example lightweight structures for fuel saving) and issues such as artefact recyclability are important for engineers to understand and to communicate to societal decision-makers (Giannakidis et al. 2015).

Engineers should also understand better the potential and limitations of the use of bio-materials in the many applications for which they are proposed, including fuels, chemical products, pharmaceuticals, treatments for waste and pollution and so on. Undoubtedly the potential for such applications is strong, and indeed some are mature already, but at what scale will it be possible to manufacture such products without impinging on food production or consuming the remaining wild lands on the Earth?

For these and many more questions, answers are hard to find. Answers that require data, analysis and consideration of complex system behaviours within hard constraints are nothing new to engineers. What is hard to find is the professional discipline to face the challenges and employ the sound analytics, like the InTIME methodology, while engaging honestly and diplomatically with stakeholders. As was noted earlier, stakes are high and decisions urgent. Is economic growth still possible? Can we adapt our existing systems, especially our transportation and manufacturing systems or is radical systems change necessary and, if so, how do we discover the feasible next steps in that radical systems change? Engineering systems designers should join those voices who call for demand-side change through increased frugality and sobriety, even a return to simpler technologies when these are the best options that fit within the hard constraints and meet the essential needs (Bihouix 2014; Krumdieck 2019).

Conclusion

This chapter has first reviewed the impacts of human activities on the Earth's ecosystems, especially those resulting from industrial societies, noting the constraints on the possible exploitation of non-renewable resources and the deleterious effects of many pollutants resulting from human activities. It then went on to explore engineering approaches that may be taken to reduce such impacts, including substitution, functional extensions in artefacts such as carbon capture and improved controls, the approaches of the circular economy and the increased role of services in the economy. Transition Engineering was introduced as a systematic approach to effecting sustainable transitions before exploring key questions that must be faced if such transitions are to be achieved.

In 1972, Donella Meadows was a member of the research team at MIT that produced the system dynamics computer model for the Club of Rome that was the basis for The Limits to Growth. Before her untimely death in 2001, she contributed, with Dennis Meadows and Jorgen Randers, to a 30-year update on the work. They concluded that their observations represented “symptoms of a world in overshoot, where we are drawing on the world’s resources faster than they can be restored, and we are releasing wastes and pollutants faster than the Earth can absorb them or render them harmless” (Meadows et al. 2001). They revisited and updated the scenarios that they presented in the original book, suggesting some general conclusions that are worth quoting here as a backdrop to the work that needs to be done by engineering systems designers (taken from (Meadows et al. 2001), numbers added here):

1. “A global transition to a sustainable society is probably possible without reductions in either population or industrial output.
2. A transition to sustainability will require an active decision to reduce the human ecological footprint.
3. There are many choices that can be made about numbers of people, living standards, technological investment, and allocations among industrial goods, services, food, and other material needs.
4. There are many trade-offs between the number of people the earth can sustain and the material level at which each person can be supported.
5. The longer the world takes to reduce its ecological footprint and move toward sustainability, the lower the population and material standard that will be ultimately supportable.
6. The higher the targets for population and material standard of living are set, the greater the risk of exceeding and eroding its limits.”

Twenty years on we have eaten into the time alluded to in (5), and point (1) may no longer be achievable, but advice on the many choices, trade-offs and targets should be a central role for engineering systems designers in the twenty-first century. This advice and the innovations in whole systems to achieve the purpose of human society will be derived through application of rigorous data and methods. All engineers in all fields should upskill and re-tool in the disciplines of engineering energy and material transitions at the earliest opportunity.

Cross-References

▶ Asking Effective Questions: Awareness of Bias in Designerly Thinking
▶ Designing for Human Behaviour in a Systemic World
▶ Digitalisation of Society
▶ Educating Engineering Systems Designers: A Systems Design Competences and Skills Matrix
▶ Engineering Systems Design Goals and Stakeholder Needs
▶ Engineering Systems Design: A Look to the Future
▶ Engineering Systems Interventions in Practice: Cases from Healthcare and Transport

▶ History of Engineering Systems Design Research and Practice
▶ Public Policy and Engineering Systems Synergy
▶ Sustainable Futures from an Engineering Systems Perspective
▶ The Evolution of Complex Engineering Systems
▶ Transforming Engineering Systems: Learnings from Organising Megaprojects

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Engineering Systems Design: A Look to the Future

35

Anja Maier, Josef Oehmen, and Pieter E. Vermaas

Contents

Abstract

Engineering Systems Design is an emerging perspective with a growing community. The preceding chapters in the Handbook of Engineering Systems Design presented the engineering systems perspective, models for describing and methods for designing interventions in engineering systems, as well as reflections on the use of those methods and upcoming practice, educational and policy

A. Maier
Department of Technology, Management and Economics, DTU-Technical University of Denmark, Kongens Lyngby, Denmark

Department of Design, Manufacturing and Engineering Management, University of Strathclyde, Glasgow, UK
e-mail: anja.maier@strath.ac.uk

J. Oehmen (✉)
Department of Technology, Management and Economics, DTU-Technical University of Denmark, Kongens Lyngby, Denmark
e-mail: jooehm@dtu.dk

P. E. Vermaas
Philosophy Department, Delft University of Technology, Delft, The Netherlands
e-mail: p.e.vermaas@tudelft.nl

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challenges. In this chapter, we are taking a look at the future of Engineering Systems Design. We start by highlighting productivity, sustainability and resilience as three societal objectives, and proceed to discuss critical paradoxes we must address through engineering systems interventions: providing a high standard of living for everyone, without paying the environmental price; a fast minimisation and mitigation of climate change without taking risks; and the challenge of global transformations respecting local needs. We continue to discuss what we consider three critical engineering systems design capabilities we must develop to resolve these paradoxes: the ability to manage systems requirements at societal scale; the development of scale-covariant engineering systems; and mastering connectability. We conclude the chapter with a call to action for researchers, practitioners and policy makers to advance theory, design methods and tools, and stakeholder outreach development to strengthen our engineering systems design capabilities.

Keywords

Capabilities · Design · Engineering Systems Design · Future Developments · Paradoxes · Resilience · Sustainability

Introduction: A Look to the Future of Engineering Systems Design

The challenges we face were never greater, nor were they more exciting and worthwhile. The contributions to this Handbook give us a basis to successfully meet them. The engineering systems perspective opens up a systemic look at the future – including the anticipation of knock-on and rebound effects of our decisions and interventions across a networked and interconnected world. How do we learn to think and act systemically? What cherished mental models do we need to abandon, and how radically do we need to re-think our economic, societal and educational models? How will we leverage our ever-increasing access to data and computational analysis to work with alternative future scenarios, understanding the sensitivity of our models, and identifying critical, systemic interventions?

Open Questions, Pathways and Paradoxes that Shape Our Future

In the opening chapter of this Handbook of Engineering Systems Design (Maier et al., 2022) we formulated five open questions for engineering systems design. In this final chapter, we focus on question three in particular. The five open questions were:

First, the question of *how to organise the coordination* of design interventions is an open question from the engineering systems perspective. On the local level, the ongoing monitoring and developing of (the local part of) an engineering system can be coordinated with standard management tools. For coordinating design interventions that occur in parallel and successively across the globe, more thinking is needed to arrive at meaningful and efficient coordination.

Second, an engineering systems perspective demands to *think about the future*. Whilst this seems obvious, it comes far from natural. Why the way we think about the future matters is because it plays a fundamental role both at conscious and unconscious levels in shaping the decisions we take now. A systems approach to the future means anticipation of the future, i.e., the potential impacts of decisions and knock-on effects of interventions in the web of interconnections. As such, the foremost open questions are: How might we train ourselves to think systemically about the future? How might we learn to act systemically for the future? Taking an engineering systems perspective is a through life learning journey.

Third, finding new ways to live within the resource constraints of the planet, creating acceptable futures for the energy and environmental needs of society, will require *system integration*, cumulative change across multiple sectors, including transport, manufacturing, agriculture, and the built environment. Rapid technology development and ensuing implications will occur in the next decades and the developments will need integration and coherent governance structures. This opens challenging questions that potentially erode our well-proven mental models of growth. Is it time to thoroughly re-think or re-cycle the economic growth model? What are the implications for us as scientists, engineers, politicians, educators, citizens?

Fourth, when addressing practitioners or scholars alike, we need to ask ourselves who is the client and who is the designer? Or, who are the clients and who are the designers? For engineers, it might seem strange to ask such questions. Yet, how might we answer such questions for the (re-)design of large sociotechnical systems that the Handbook is about? Society is the client, or, accepting plurality in our current world, societies are the clients. And we all are designers. Each and every one of us has to play that role. How might we raise awareness that *responsibility lies with everyone*? Consequences and implications of our actions originating in the past, taken now, implicate future generations. Hence, linking to the above, we need to train ourselves to lead *from* the future, to become system stewards. This challenges us all, as it impacts deeply on personal levels to change our behaviours.

Fifth, open questions include how we might bring latest research insights together with practice-based implementation. If we want to educate leaders, we have to take a larger point of view, a systems point of view. If we want to empower engineers in positions of authority, we need to change engineers *education* towards a more balanced educational model, throughout the life cycle of a person's career, starting with school and university. Engineering systems design is *through life learning*. This also means creating a skilled workforce, upskilling, re-skilling across work sectors, across work disciplines. We all need new skillsets of how we think and talk about situations, about potential solutions. What perspectives we highlight, regardless of talent, knowledge, time, technological foundations, and investment, we need to create valuable opportunities for collaborations ahead. And in this, one of the main open questions then is: How do we learn and train our ability to connect, and disconnect for that matter, i.e., to master *connectability?*

The contributions to this Handbook serve as a basis to answering these questions, but it is fair to say that giving full answers requires further research. In this final chapter we make a start with considering three paths that open when considering the third question discussed above. These paths are:

Economic Productivity: We have to re-think – and re-design – the relationships of quality of life, wealth, growth, and consumption. We have to rethink the time-scales that determine our investment decisions – is it quarters, years, decades, or centuries? We need to re-evaluate how we think about societal utility – is it maximising value, or minimising regret? How might we decouple economic growth from resource consumption? And we have to answer the question of global fairness: Not just the distribution of tangible and intangible productive factors and the resulting gains, but also the reconciliation of local and global needs – and the rights and powers to effect global change.

Environmental Sustainability: We must evolve the concept of planetary boundaries from theory to actionable designing. This includes moving from a carbon-cycle focus to an approach that addresses all critical environmental processes and does justice to the closed-system nature of our environment. We have to engage in conversations to move from a sustainability to a regenerative mindset, as we have missed the opportunity to avoid critical harm to the environment. We have to develop the capacity to link our intrinsic motivation to make selfish choices to choices that actually benefit us personally in the long run – including nature enlarging itself again.

Societal Resilience: Engineering systems must work. Interventions in engineering systems must be successful. And they must do so under practically unpredictable circumstances across decades. Resilience allows us the freedom to have success even when we cannot predict the future. We will learn to design our engineering systems to operate under evolving conditions and constraints, and we will learn to embody long-term societal ambitions and goals even if we do not know the final design answer yet. Instead of offering the one best solution, we design fluidity, modularity, and connectability into our conceptualisations and solutions. That includes classic system capabilities at an engineering system scale, such as robustness against sudden shocks, the ability for graceful degradation, and the scalability to rebound quickly. But it also includes strengthening social cohesion of our societies to enable respectful and fact-based discussions and decisions on directing large investments, and fairly distributing their pains and gains. The engineering systems perspective helps shaping and accommodating technical constraints to achieve societal objectives.

Addressing these three path will be difficult, since they are interrelated and require us to overcome a number of paradoxes:

Paradox 1: A high standard of living for everyone without paying the environmental price.

We still live in a world characterised by stark differences in the standard of living – measured in economic terms, but also measurable in terms of education, equality, or health outcomes. While we must strive to build a more equitable world, attempts to do so in a "business as usual" approach will irrevocably destroy that world. The emergence of this first productivity paradox is straightforward: If we were to export the standard of living of the developed countries across the globe, using the same models of production of goods and services, we would dramatically accelerate our environmental decline: 25% of the world population account for 75% of the resource consumption. The business as usual approach triples our environmental footprint – hence we must look for alternatives. These alternatives present us with an economic productivity problem, as we would like to maintain and expand our standard of living. They represent also an environmental sustainability problem, as we need to reduce our environmental footprint drastically – not by a few percent. And they present a societal resilience problem, as societies will be facing transformational changes on these alternative approaches.

Paradox 2: Fast minimisation and mitigation of climate change without taking risks.

The latest global commitments to achieving a step-change in environmental sustainability relies heavily on technological advancements. Effort to realise this change range from a hydrogen economy, to the establishment of 'energy islands', to carbon sequestration and storage techniques, to a widespread electrification of transport and heating, and – at least in some countries – to a renewed interest in advanced nuclear fission and fusion concepts. In short, we need to re-design, re-build and learn to "re-operate" significant parts of our critical infrastructure, especially our energy infrastructure, with technologies we have – more often than not – not yet deployed at a national or global scale. Attempts to do so with our "business as usual" approach again confronts us with a paradox. This approach is a slow one for good reasons such as managing and resolving technology (and system) readiness risks. Yet, the question is do we need to deploy new technologies fast, at scale, and in critical areas such as energy, for meeting the sustainability problem? Or is a low-tech approach (e.g., Bihouix, 2020) the way forward? That confronts us with the economic productivity problem, as the transformation and 'creative destruction' of existing industry sectors – not just single companies – and the growth of novel supply chains in their place. And it presents a life-or-death societal resilience problem, as we cannot compromise on the resilience of our critical infrastructure nor loose support in society for the fast changes.

Paradox 3: Global transformation respecting local needs

In dealing with these problems, we also face a significant geopolitical paradox, or amalgamation of paradoxes: Global responses to the challenge of environmental sustainability may easily have hard local ramifications, for the impacts of climate change, and other environmental sustainability challenges outside of the carbon cycle, do not necessarily geographically coincide with the activities that fuel those problems. Lagos in Nigeria, and Haiti, for example, will be the areas hardest hit by rising sea levels and extreme weather, while they contributed very little globally to the problem, nor are they in a position to shape the global response to reduce our impact, and mitigate and adapt to its consequences. Global action for addressing the environmental sustainability challenge may in this way easily damage societal support for this action. Another geopolitical paradox lies in the integration of global value chains that have underpinned unprecedented growth in the last decades, but also leading to questions of national autonomy and the dependency-price incurred by this integration. This is cause for obvious economic productivity challenges, if we were to reconceptualise global supply chain structures, or if we were to account for the externalised cost of climate change. The sustainability challenges centre around the asymmetry of cause and effect, and the challenges of precisely predicting local impacts and designing mitigation and adaptation actions. The resulting resilience challenges raise crucial questions around global perspectives on the 'fairness' of sharing of burdens and investments, and how those mechanisms will shape global political, technological and economic cooperation.

The engineering systems design perspectives presented in this Handbook offers several perspectives on how to tackle these challenges – after all, system thinkers and designers embrace paradoxes. They encapsulate unmet design needs of the engineering systems underpinning our societies and force us to look for novel solution directions. In the next section we explore in a more conjectural manner a few ingredients of how engineering systems design can advance for addressing the three pathways and escape the described paradoxes.

Developing Capabilities to Design the Engineering Systems of the Future

We believe that we need to develop three core capabilities in our engineering systems design portfolio: Managing system requirements at societal scale, designing scale-covariant systems, and making connectability a core systems capability.

Managing System Requirements at Societal Scale

We must learn to master requirements for engineering systems interventions. That includes dealing with the uncertainty, technical complexity, and the social dynamics of defining a desirable future. This is at the heart of creatively resolving our productivity, sustainability and resilience paradoxes: Clearly articulating the legitimate needs of all stakeholders.

Requirements – as a representation of stakeholder values and priorities – are at the very heart of every engineering activity, both social and technical. Reflecting on the largest challenges facing us today and for the foreseeable future – for example reducing our environmental footprint, adapting to a changing climate, facing global health challenges, addressing inequality – a number of issues emerge regarding engineering systems level requirements management. First, we are facing unprecedented levels of uncertainty. This is, in large parts, not "just" driven by rapid global changes. In fact, we can argue whether the rate of change really is increasing. But what is increasing due to the global nature of the challenges we face are the number of factors that need to be considered – and thus the number of uncertainties.

This uncertainty is not only present in future technological or economic trajectories, but also fundamentally in our vision of the future: How are we supposed to imagine something that is too big to imagine by any single person? How do we reconcile the fact that we need to predict the future in order to plan appropriate actions, but also monitor real world developments and adapt accordingly? Second, upholding the fundamental notion of a technocratic, i.e., formal and fact-based, decision-making processes becomes increasingly difficult. We are facing problems of "deep uncertainty" (Oehmen and Kwakkel 2022), where we do not fully understand the underlying causal pathways. How exactly will the climate change? How exactly do interventions in developing countries translate into health outcomes? How exactly can we scale up low-carbon energy sources globally? This makes it very difficult to implement our established best practices – including those discussed in this handbook – that we have developed to address highly complex problems. Because we are subject to bounded rationality, we need to share the problem-solving across many actors. In addition, a good number of stakeholders are not primarily interested in finding a compromise solution, or even particularly interested in understanding and presenting the complexity of the issues we are facing. The skilfully manufactured perception of uncertainty – the exaggeration of real uncertainty, but also the doubting of facts – is a powerful force in public discourse.

Closely linked to this challenge is the issue of stakeholder diversity, and the associated diversity of values. The assumption that long conversations and discussions will always lead to agreements is, at best, naive. A coal miner has valid, serious and urgent concerns regarding the phase-out of coal power stations. As we start including compensations for the negative value that our designs have for some stakeholders, we start a cascade of interlinked design challenges that lead to a significant increase of scope. This further complicates the question of "what is our problem" and "what are our requirements", as the problem scope naturally cascades along our understanding of both the problem root causes, but also along the development of our solutions. In addition, it further complicates reaching a robust consensus.

This challenge also has also a strong temporal aspect: We cannot understand every detail at once, we cannot make every change at once, so we will also not reach every stakeholder at once – both in terms of positive and negative consequences. This has a profound implication, as we can no longer conceptualise a design task as a 'project' with a well-defined objective, start date, end date, and specific resources. How do we decide as a society to embark on a challenge where we do not know where we will end up, or when we will end up there, or how much it is going to cost?

A possible way out of this challenge that we see is to decompose and separate out design tasks on societal scale. Engineering Systems Design must acquire in the future the tools and methods to decompose design tasks. We have to develop "partial design" capabilities that introduce system architectures allowing us to implement modular, incremental and local solutions. In regular engineering design these decomposition tools already exist and are modular design endorsed. Engineering systems design should and are adopting these tools and expand them also to the societal realm of engineering systems. The main objective is to respect our bounded rationality, both as individuals, but also as our capability as a society to address multi-faceted, complex issues. While we are increasing the complexity capabilities of our toolboxes, we must respect that there is only a certain level of complexity that can be meaningfully discussed and decided in an open society. Decomposition – and "disconnection" – of problems, as well as modularisation – and "connectability" – have to support an informed and system-oriented conceptualisation of our design challenges.

Towards Scale-Covariance of Engineering Systems

We must consider designing engineering systems for "scale covariance," that is, designing engineering systems in a way that they have the capability to operate efficiently at different geographic and economic scales. Scale covariance addresses the societal resilience challenge and is a way out of the geopolitical paradox that engineering systems that are effective on a global scale introduce ineffectiveness due to political dependency.

During the period in which we composed this Handbook, the resilience – or the lack thereof – of engineering systems became visible by global and local events. In the beginning of 2020, the Covid-19 pandemic broke out and in March 2021, on an arguable less life-threatening scale, the Suez canal was blocked for 6 days. Then, in February 2022, as we were going to print with this chapter, Russia invaded Ukraine. These events made clear that engineering systems indeed have global size and are thus also vulnerable to global disruption. Supply chains and manufacturing processes got interrupted, the consequences of which started cascading through the world. In case of the Covid-19 pandemic, the disruption concerned even the very engineering systems that should be part of the response to the pandemic, such as medical supplies and industrial infrastructure for creating medical devices. And even when taking distance from any nationalist rhetoric and geopolitical struggle: the events make clear that the knock-on and rebound effects in engineering systems are more than real, and are making engineering systems quite vulnerable.

A way out of this vulnerability is to design engineering systems in a way that their effective operations is *scale covariant*. Individual engineering systems may have an optimal scale for their operation, which may be regional, national or international. Due to the globalisation, numerous engineering systems are operating on a global scale. The manufacturing systems for medical supplies and devices are cases, and so are – as also illustrated by the Covid-19 pandemic – the manufacturing of high-tech components such as computer chips. This global scale also introduces vulnerabilities to engineering systems. If these engineering systems only operate effectively when running globally, global disturbances ranging from an unsuccessful manoeuvre with a container ship to geopolitical struggles may make the operation of the engineering systems less effective or even bring them to a halt. One way to avoid these vulnerabilities is the imposition of strong international coordination for taking away disturbances and avoiding that nations can withdraw their contributions for nationalistic or geopolitical reasons. An alternative - and more realistic- way is to design scale covariance into engineering systems, that is designing these systems for the ability to operate sufficiently efficient also when they run on a scale that is different to (that is, smaller than) their optimal scale. The internet is in principle an example since it is a system that still runs effectively if (larger) parts of it stop to work. With scale covariance, disturbances – by accident or intentional – stop to harm the running of engineering systems; the systems can scale down in size and still run effectively though possible a bit less efficient than before the disturbance. And when the disturbances are overcome, the engineering systems can, again by scale covariance, veer back into its larger optimal shape. Additional advantages of covariance are that parts of engineering systems can be temporarily disconnected for maintenance of redesign. Renewal of engineering systems can be done since others can disconnect without much problem if something goes wrong. Scale covariance can in that way contribute to the modularisation of engineering systems as called for above.

Towards Mastering Connectability

A key enabler for system integration is to ensure and master connectability – and the ability to intentionally disconnect where appropriate. Engineering systems are partially designed and partially evolved. By extension, this may mean that linkages are intentionally designed and also emerging. We argue that we need to actively master connectability – the ability to connect – and that means to actively think through emerging dynamics.

The Handbook offers multiple strategies for interface management, for connecting and for disconnecting. This includes values alignment, various jointing techniques and design strategies such as modularity, partial decomposition, configurability, design for technical change, design for behavioural change, designing for evolvability and more. So far, we argue, connectability has not been actively paid attention to. Explicit training in the ability to connect, i.e., connectability means also having the ability to designing connections that endure the test of time that are the basis for evolving forward.

So, what do we mean by connectability and why is it important? To go forward, our proposition is to learn, to train, and to practice *connectability* and designing connections. Our thesis is that we need to know how to connect in order to disconnect. Otherwise, we will not be able to anticipate and properly think through implications of our decisions, consequences, foreseen or unforeseen, of our decisions or non-decisions. The inverse is not true. Knowing how to disconnect, or disconnecting, does not mean we have the ability to connect. In other words, disconnecting does not mean we know how to re-connect. Yet, we should. Hence, we need to train our ability to connect, i.e., connectability.

To give an example of a disconnect giving rise to emerging (unforeseen) consequences, Brexit springs to mind. Against the hopes of many voters, it has made mobility harder, the difference between rich and poor more pronounced, i.e., the disconnect more pronounced. Back to our thesis above, disconnecting does not mean we know how to (re-)connect. Lately, turbulent geopolitical developments have been very tangible with the post pandemic business and political world being dramatically different from what we have expected two decades ago. Now, with disconnections, embargos, sanctions, travel restrictions, impacting every part of our lives, how to ensure to stay connected going forward? Or even, how to ensure to re-connect?

Therefore, we propose to learn and train how to master connectability, designing connections, as a main trait of a systems thinker and doer. So, how might we train connectability, so that we can intentionally disconnect where appropriate while maintaining the ability to connect where needed? One way is through structural coupling, i.e., through understanding the 'logic' or 'code' of how systems operate; the 'pulse' with which systems evolve: The first thing to do is to acknowledge that Society as a social system is based on differences and competition (competing interests). Society is a set of functionally differentiated sub-systems (e.g., Luhmann 1995), such as the economy, education, science, politics, law, art, and so forth. Such systems reproduce themselves by themselves. The economy reproduces itself every time we need to buy consumer goods, have to buy to replace, and, as such, the economy keeps itself going. Such systems follow their own logic, their own code. For the economy, the code is 'having money/not having money', for law it is 'right/wrong', for science it is 'true/false', and so forth. The logic of different systems can be connected. For example, art can have monetary value, the economy can check-up law, etc. Fundamentally, the operating code is different and Society is constructed of multiple realities, such as a legal reality or an education reality, with many dimensions to each problem. So, based on this realisation, a strategy to train the ability to connect – connectability – is through structural coupling; through learning to understand the underlying 'code' based on which decisions are made, and/or each proposition is weighed up against.

Conclusion: A Call to Action for Adopting the Engineering Systems Design Perspective - Implications for Research, Practice and Policy

We believe that as a research, practice and policy community, we must take three steps towards designing effective engineering systems interventions.

1. **Theory development for engineering systems design**: In the introduction to this book, we have defined some fundamental terminology for discussing engineering systems and engineering systems design. Each chapter in this Handbook – especially from Parts I, II and IV – has contributed to such advancements. We must actively build on those strong foundations. Theorising and theory building is an area of very active development in the general field of design, driven by both a practical need of supporting design innovation, as well as an academic necessity of continuously refining design-related research quality (e.g., Cash 2018). This means that in our area of engineering systems design, we must continue our work to explain (1) the concepts, constructs and principles; (2) the types and causality of their relationships; and (3) our ability to predict engineering system design

outcomes for a range of scenarios. The fact that engineering systems design touches a large number of practice and research domains makes this challenge significantly harder – and more interesting.

2. **Development of engineering systems design methods for theory and practice**: In this book, we have laid out our and the community's current responses to the very practical challenges of modelling and describing engineering systems (Part II) and re-designing engineering systems through interventions (Parts III and IV). As this book demonstrates, we do have a significant head-start in this space – but we believe this Handbook also shows that there is significant work still to be done. The paradoxes that we formulated above illustrate just how complex a task we are taking on. The three major capabilities we propose – developing a capability to manage requirements at societal scale, leveraging co-variance of engineering systems design solutions, and emphasising connectability – all illustrate concrete needs in the development of modelling and design methods. The fundamental challenge remains: How can we cleverly tackle a global, complex design task with local, understandable solutions? How can we productively engage the global and diverse stakeholder landscape that genuinely has very different – and often currently opposing – needs? How can we manage across timescales, from taking urgent actions now for benefits decades or even centuries in the future? And at the end of the day, how can we become effective system designers who leverage dynamic system behaviour and understand, accommodate and use adaptive behaviour and unintended consequences?
3. **Engaging the global stakeholder landscape**: It is "easy" for researchers to emphasise the need to strengthen our global educational capabilities for engineering systems design. But it is important. How can we – practically – develop, coordinate and communicate research agendas and educational programmes? How can we transform our current educational offerings at universities across the technical-, natural-, social sciences, arts and humanities? And most importantly, how do we provide education, learning and opportunities to capture and exchange best practices across the life cycles of careers (see Part V of this book)? Increasing the impact and scaling engineering systems design education is, however, only part of the challenge. The broader goal is: How do we effectively leverage engineering systems design practices across society? This starts with engaging organisations that are actually, today, engaged in engineering systems design tasks, facing the paradoxes we described earlier – and doing their best to solve them? We have taken the first steps as part of this book (see Part IV) and much more remains to be done to understand the actuality of engineering systems design challenges. Last but not least, this extends to reaching and involving policy makers and those holding public office in bringing engineering systems design capabilities to tackle global challenges.

We believe that the global community – researchers, practitioners, and policy makers – are rising to the global challenges of our time. We must acknowledge and embrace the complexities and paradoxes of our situation and thoughtfully develop the mindsets, methods, and tools we need to resolve them. We hope that this Handbook of Engineering Systems Design is a step in that direction.

Cross-References

► Introducing Engineering Systems Design: A New Engineering Perspective on the Challenges of Our Times

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