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

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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- and 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.

KeywordsDigitalisation -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 wasn’t 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 sociotechnical 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 the final chapter of the Handbook, *Engineering Systems Design: A Look to the Future*, 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 the closing chapter *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 the chapter "*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. The chapter "*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 "*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. The chapter "*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: "*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 I of the Handbook, the chapter "*Systems Thinking: Practical Insights on Systems-led Design in Sociotechnical 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 the chapter *"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, the chapter "*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. The chapter "*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, the chapter "*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 the chapter "*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, the chapter "*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 the chapter "*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 "*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 "*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. The chapter "*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. The chapter "*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, the chapter "*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 sociotechnical safety, "*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 the chapter "*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 "*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, "*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. The chapter "*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. The chapter "*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. The chapter "*Asking Effective Questions: Awareness of Bias in Designerly Thinking*" emphasizes 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? "*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, the chapter "*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.

The chapter "*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 "*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 the chapter "*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. The chapter "*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, the chapter "*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.

The chapter *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. The final chapter "*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.

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