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DOI
10.1007/978-3-030-46054-9_31-1

Publication date
2022

Document Version
Final published version

Published in
Handbook of Engineering Systems Design

Citation (APA)
Maier, A., Oehmen, J., & Vermaas, P. E. (2022). Engineering Systems Design: A Look to the Future. In A. Maier, J. Oehmen, & P. E. Vermaas (Eds.), *Handbook of Engineering Systems Design* (pp. 1-12). Springer Nature. https://doi.org/10.1007/978-3-030-46054-9_31-1

Engineering Systems Design: A Look to the Future

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 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

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A. Maier et al. (eds.), *Handbook of Engineering Systems Design*,
https://doi.org/10.1007/978-3-030-46054-9_31-1

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 (Part 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.

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