Chapter 7
Outlook

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Bertolt Brecht once closed a text with the words "We are disappointed to see the curtain close and all questions are left unanswered" [1]. In this book, it has become clear that uncertainty is immanent in the product life cycle of technical systems in mechanical engineering from (B) production, (C) usage, (D) reuse to (E) sourcing. The latter is the starting phase of the following sequence B, C, D, E. Uncertainty has been relevant since the beginning of the industrialisation, cf. Theodor Fontane's ballad 'The Tay Bridge' quoted in Chap. 1 and this will continue to be so. Hence, we will never see "the curtain close", but a perpetual contribution of engineering science, applied mathematics, law and further branches of science to master uncertainty in mechanical engineering.

7.1 Towards the Complete Picture

The product life sequence B, C, D, E spans the temporal dimension. The spatial dimensions are captured by the system boundary. With further increasing system boundaries, we go from material to component and from techno-economic to socio-technical systems. In this outermost system boundary, market forces, social impact and regulatory rules become prominent.

In the presented book, we focused on (A) product design and the two phases (B) production and (C) usage of the product life cycle, cf. Fig. 1.6. Of course, this is not the complete picture: mastering economic uncertainty and uncertainty in acceptability, inevitably needs a holistic view on the product life sequence on the one hand and the extended system boundaries on the other hand, cf. Fig. 7.1.

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P. F. Pelz et al. (eds.), *Mastering Uncertainty in Mechanical Engineering*,
Springer Tracts in Mechanical Engineering,
https://doi.org/10.1007/978-3-030-78354-9_7

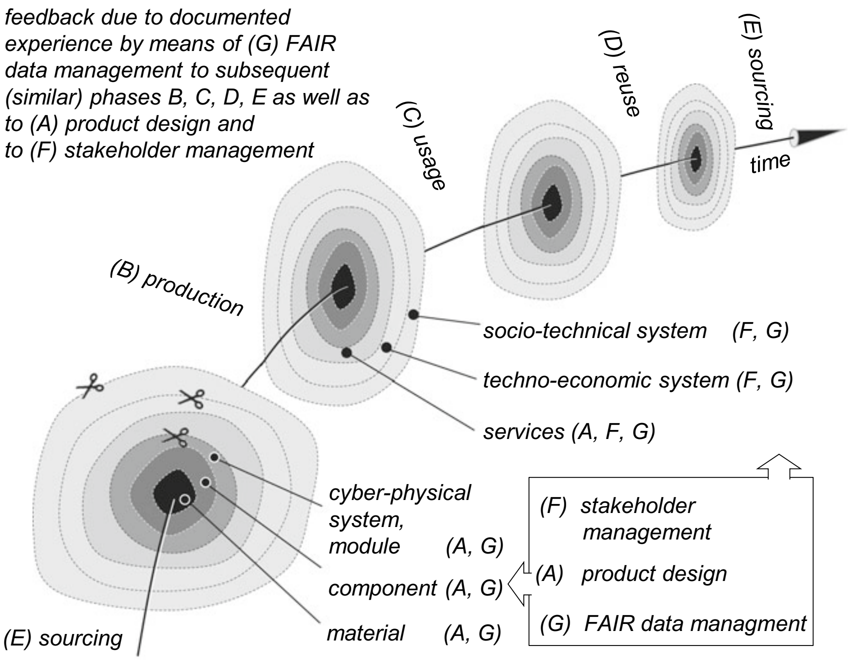

Fig. 7.1 The product life sequence B, C, D, E—rather than a cycle—is represented by the four phases (B) production, (C) usage, (D) reuse and (E) sourcing. The spatial dimensions are captured by the system boundaries extended from material to the socio-technical system. The phases (A) product design, (F) stakeholder interaction and market regulation as well as (G) FAIR data management address all temporal phases and system boundaries as indicated. The trajectory of the system in a Lagrangian representation shows the individuality of each system composed of individual components. The cloud symbolises the Eulerian observer fixed in space. This change of reference enables the feedback to subsequent similar phases as well as to (A) product design and (F) stakeholder management. Hence, (G) FAIR data management enables on the one hand learning from previous similar events; on the other hand it enables transparent quality KPI

It is evident that the relevant time period, the product life sequence, includes the phases (D) reuse/recycling and (E) sourcing. The second law of thermodynamics teaches us that there are no real systems without impact exceeding the phase (D) reuse/recycling [4]. Hence, it is indeed better to speak of product life sequences B, C, D, E, B, C, D, E … rather than a product life cycle.

The spatial extension of the system boundary from material, cyber-physical components, systems and services towards techno-economic or socio-technical systems needs not only contributions from (A) product design. Understanding and possibly control of (F) stakeholder management is as relevant as the (G) FAIR data management, where FAIR is the acronym for Findable, Accessible, Interoperable and Reusable. Stakeholder management includes analysis and control of stakeholder interaction as well as instruments for market regulation and market surveillance. As such, negotiating contracts is part of stakeholder management; the analysis of stakeholder interaction typically is a field of interest for sociology but also for economics and political science.

Some aspects of the extended view were indeed addressed in this book. Chapter 5 is exemplary for this. Mastering uncertainty in the assignment of functional requirement specifications and quality objectives needs the understanding of the stakeholder interaction combined with market regulation. The same is true for existing and emerging legal constraints. It is expected that digital humanities will influence this field in the future even more.

We are aware that Sustainable Systems Design, as discussed e.g. in Sects. 1.6 and 5.1.1, requires a holistic approach, i.e. the extension of system boundaries to socio-technical systems. Therefore Fig. 7.1 complements Figs. 1.10, 5.2 and 5.3. In short, sustainability can only be assessed from a combined socio-economic and technical perspective. Integration of these perspectives is essential for future research.

(F) stakeholder management, combining stakeholder analysis and market regulation, named side by side with (A) product design is part of economics, sociology and law. The scientific methods in that field stem e.g. from cybernetics or applied mathematics. Game theory is one branch of applied mathematics being beneficially applied to stakeholder analysis [3].

(G) FAIR data management [2] is an enabler for transparency in quality key performance indicators (KPI) to foster acceptability. Hence, the quality dimensions (i) effort F_1 measured in economic and social cost, (ii) availability F_2 and (iii) acceptability F_3 need to be further developed as enablers for Corporate Social Responsibility (CSR). These objectives apply to data, software, but also to already existing conclusions. FAIR data management requires (i) data competence, (ii) information technologies and (iii) data governance and curation. Therefore, FAIR data management is the prerequisite for the process from data to wisdom; it leads to a living digital twin being represented by a graph with persistently identified subjects and objects as nodes. The edges represent the predicate, i.e. functions mapping the data from the subject to the object. The graph in combination with a consistent ontology allows accessibility and reusability of the data.

With regard to the interaction between the interest groups, the consumer market differs from the capital goods market in the actors involved. For the former, these are manufacturers, planners, owners/operators and society. In the case of infrastructure systems, the number of stakeholders is further increased because owner and operator are usually not identical and different infrastructure systems are usually coupled. This considerably increases the complexity of stakeholder interactions. In the case of consumer goods, the acting stakeholders are usually limited to manufacturers, retailers, digital matchmakers, customers and society. In both cases, with or without online platform markets, it is clear that emerging block-chain based digital currencies will change the interplay between markets and stakeholders.

Components of production systems or fluid systems are traded on the capital goods market, a typical business to business market. The composed systems enable functions, such as producing, transport, heating, and many others. Mostly, these are typical infrastructure systems with (i) complex stakeholder interaction and market regulations, (ii) frequently unclear functional requirements and quality KPI as well as (iii) an only beginning smart modularisation.

7.2 Future of Mastering Uncertainty

This book builds on the tradition of Taguchi's robust design method, which has been used since the 1960s. At the same time, the world has continued to develop over the past 60 years, and the past 10 years in particular have seen significant new contributions to the mastering of uncertainty. Many of them are presented in this book, to name only some keywords:

(i) Rigorous classification of uncertainty,
(ii) extension of the system boundary towards socio-technical systems,
(iii) validated methods for mastering data, model and structural uncertainty and
(iv) active components serving mastering uncertainty in load-bearing systems.

It took two decades for Taguchi's methods to spread. The dissemination time of the presented newer concepts will be shorter for several reasons: First, the needs of society and the emergence of CSR are becoming powerful drivers for mastering uncertainty; second, digitalisation and computer power enable new methods, technologies, and strategies for quantifying and mastering uncertainty as presented in this book.

Our main focus has always been on mastering uncertainty. The three strategies to be most important in mastering uncertainty are

(i) design and operate robustly,
(ii) gain flexibility and
(iii) enable resilience.

There is still much to do for gaining robust, flexible, or resilient technical systems. In the following three sections, we anticipate the future regarding (i) to (iii).

7.2.1 Robustness

Section 6.1 illustrates that a wide range of methods and technologies is now available to master uncertainty through sufficient robustness. For both aspects, first uncertainty quantification, and second robust optimisation of components and systems, there is a need for multi-purpose, easy-to-use software frameworks. First and in more detail regarding uncertainty quantification: a software framework is needed supporting a consistent workflow from the quantification of uncertainty within the product design phase, to the propagation of uncertainty in the production phase and to the prediction of the system's reliability in the usage phase. Within this framework, efficient probabilistic parameter calibration methods, e.g. in a Bayesian framework, shall be available to cope with the increasingly complex and computationally intensive models used in the further virtualised product design. Second and regarding robust optimisation of components and systems: available mathematical methods are currently not supported by general purpose software, and prior modelling based on human experience is needed before using it for practical problems. Both facts still inhibit Sustainable Systems Design.

We expect software technologies to close this gap in the near future. Yet, there are still open research topics. The first addresses mathematical research, the second engineering research. Above all, the mathematical tools that enable robust optimisation, as described in Chap. 6, all exploit the underlying structure of the problem in one way or the other. Extending these methods to systems for which the corresponding mathematical structure is different, lacks refined methods and therefore requires mathematical research. Thus, although robust optimisation has developed into a relatively mature field with many contributions, there are still many open research questions, in particular for problems of practical interest, such as dynamical, i.e. transient problems.

As has been seen in Chaps. 1, 3 and 6, Robust Design and the related Sustainable Systems Design as it is understood here, can be seen as solving a constrained optimisation problem with the specified systems function as one constraint to be solved for a given design space. The objective has three dimensions: effort, availability and acceptability. To master uncertainty in the customer expectation, in material or component properties, usually an increase of effort, e.g. regarding material consumption, is needed. Section 3.5 listed seven inherent Robust Design and operating concepts that potentially offer additional freedom of design without additional cost and weight. Thus, tailored material or component behaviour could be one promising approach with graded material or component stiffness. Also the deliberate use of residual stresses potentially offers additional freedom of design without additional cost and weight.

When it comes to systems, the robustness of individual modules or components is strongly influenced by the behaviour of other components of the system. Thus, the application of Taguchi’s DoE method as one tool of the Robust Design methodology can become quite expensive. Therefore, a further important research area is the efficient and comprehensive validation of a module’s robustness under simulated realistically detuned operation and installation conditions.

In contrast to resilience, robust systems do not show recovery phases. Hence, robustness is achieved mainly by “smart” decisions made in the (A) product design prior to the product life sequence B, C, D, E. In the future, merging of data gained from experiences made in the product usage or a physical or cyber-physical product validation test with prior knowledge will become much more important. This merge will result in grey-box models enabling the mentioned “smart” decisions. Indeed, there is a need for integrating Bayesian methods with Robust Design and risk assessment in product design.

7.2.2 Flexibility

Section 3.5 introduced the concept of flexibility and Sect. 6.2 depicts promising approaches for mastering uncertainty by increased flexibility. At the same time, it also reveals the additional costs and complexity of design and production processes concomitant with higher flexibility. Further research work is necessary to provide either (i) smart modules or (ii) smart modularisation, cf. Sect. 3.5, which allows for the highest flexibility at a specific minimised cost. One promising approach for future developments could be the application of lean design engineering principles to obtain flexible systems.

First, smart modularisation is an interesting application field for optimisation methods presented in this book. Second, smart modules usually incorporate semi-active or active components within complex technical systems. They offer a freedom in usage and by this cover different customer needs or expectations. However, the reliable mastering of uncertainty, e.g. by the methods presented within this book, is necessary to, on the one hand, legitimate the increased effort associated with the semi-active and active components and, on the other hand, increase the acceptability for the customer and within society.

The current driver for modularisation is the speed when scaling up as well as satisfying customer demands. Functional units are integrated into modular type packages fulfilling a functional requirement specification. Further open questions are automated documentation as well as the approval processes. From a Sustainable Systems Design perspective, as defined here, it is clear that the specified function will be a constraint, whereas the minimisation of social costs measured in energy or material consumption will be an objective. This demands the definition of metrics and the aggregation of quality KPI from the component level up to the business level. Thus, commissioning, approval and learning will be enabled by FAIR data management as specified above.

7.2.3 Resilience

As discussed in Sect. 6.3, robust systems do not show a recovery phase after a severe impact, whereas resilient systems do. Besides seldom exceptions, only smart agents, humans or cyber-physical modules enable a recovery phase being characteristic for dynamically resilient systems. Those agents heal severely experienced damage by having the ability to measure, react, learn and anticipate.

We can imagine that in a composed system, agents interact in such a way that each agent measures its surrounding and all agents together react in a self-organised manner. This vision can be seen as a biologicalisation of products and processes. The driving potential for the agents to act is the loss of functional quality, cf. Chap. 1. From this perspective, the recovery phase of the resilience triangle is a Continuous Improvement Process (CIP) of products or the product design phase. Only now, the latter takes place within the usage phase. Hence, in this picture of dynamic resilience (A) product design becomes integrated into the product life sequence B, C, D, E mentioned above.

There are few examples of self-healing materials, components or systems without cyber or real agents. In Sect. 3.5, liquid sealant added to the inside of a tire was mentioned as one example: a puncture is self-healed by this sealant; a wooden boat seals itself by swelling the wood; a leather boot automatically seals small holes. In the named examples swelling is the basis for self-adaption or self-healing. In nature we observe stress-induced shape optimisation inline and online integrated in the life sequence B, C, D, E. Today, we use such shape optimisations offline in the (A) product design. Also here, the future task is to integrate (A) product design in the (C) usage phase as nature does. From this we conclude that the design of self-healing materials or self-repairing machines could be stimulated from nature. Their integration into technical systems could pave the way to the so far difficult to achieve recovery of structures.

In Sect. 6.3, static resilience is distinct from dynamic resilience: static resilience is the property of a system predefined by the system's design; dynamic resilience is the skill to react to a loss of functionality. The degree of static resilience e.g. of a water supply network is established in the (A) product design. The future will focus on the trade-off between static resilience and the costs achieving this static resilience. Our current research shows that there is a saturation of gained static resilience versus costs as one would expect. Still, there are open questions regarding the resilience of networks.

Mathematical tools to optimally design resilient systems have been developed for a long time, often under different names like network survivability, etc. The corresponding problems are inherently multi-level and an exploitation of the particular structure is necessary in order to be able to solve the corresponding optimisation problems. Similar to robust optimisation, the future is likely to see a refinement and extension of the available tools and hopefully software support. Moreover, incorporating learning into the systems poses interesting mathematical challenges.

7.3 Final Remarks

Our approach is mainly based on the creation of white-, grey- and black-box models and the use of those models for algorithmic supported systems design. The composition takes place for a known design space. We fully acknowledge that uncertainty sometimes can also be mastered by out-of-the-box thinking, cf. Chap. 1, where out-of-the-box means outside the known design space. Improvisations leading to processes and designs not foreseen in the originally created design space can definitely be stimulating and often help to create new break-through technologies and designs.

Although this book is based on Ratio and Reason, Intuition and Inspiration are the most important drivers. In that respect we are in agreement with the British empiricist

David Hume and others, cf. Sect. 1.3. The systematic development of the necessary creativity could be an important topic for future engineering education.

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