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Design perspectives, theories and processes for engineering systems design

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B. Abstract (approximately 150 to 250 words)

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

C. Keywords (Please provide suggestions for keywords required to facilitate search of chapter on web. A maximum of 5 keywords will be finalized by the Editors)

design, design perspectives, design theory, design process, engineering systems, engineering systems design

1 Introduction

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

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

A good example of an engineering system, which we discuss throughout the chapter and that we have also worked on, is an aircraft and its role as part of a transport solution. A century ago the main design problem was how to master the flight physics of the aircraft itself (Vincenti 1990), ensuring that propulsive power was sufficient and that structural integrity was ensured. Today, the design challenge in air transport is to design and deliver a sustainable, zero-carbon transport solution within a few decades, see e.g. (Acare 2011).

1.1 Overcoming disciplinary boundaries in engineering systems design

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

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

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

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

1.2 Multiple views on an engineering design system

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

Figure 1 Multiple views and levels of detail of aircraft systems design

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

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

1.3 Engineering systems as sociotechnical systems

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

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

(1) Its component system[s] fulfil valid purposes in their own right and continue to operate to fulfil those purposes if disassembled from the overall system, referred to as “Operational Independence of the Components” and
(2) The component systems are managed (at least in part) for their own purposes rather than the purposes of the whole, referred to as “Managerial Independence of the Components”

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

An aircraft, as a system, consists of a large number of subsystems that in turn are organised into modules, parts and components. The engine is for example one of about 18 different subsystems of an aircraft (the precise number depends on the level of decomposition) together with wings, fuselage, landing gear and so forth. Each of these are typically complex enough to be labelled systems in their own right, but when viewed from the aircraft context, they are defined as subsystems. The aircraft is not a System of Systems from the perspective these subsystems according to Maier’s (1998) definition, since the subsystems do not continue to operate and fulfil their purpose if removed from the aircraft.

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

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

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

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

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

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

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

1.4 The role of design perspectives, theories and processes

The design of sociotechnical engineering systems is a highly complex process without clear boundaries, which the different stakeholders approach in their own ways and from their own perspectives. Design, like any complex system, can only be understood in its entirety at a high level of abstraction or by adopting specific perspectives which shine a light on some aspects of design while subsuming others. The relationship between theories, perspective and processes is illustrated in Figure 3.

Figure 3. For the purposes of this chapter, we here distinguish between perspectives on design, which each emphasise a particular aspect of sociotechnical design, and design theories, which aim to be formal in the sense that the formality of an expression is defined as the invariance, under changes of context, of the expression’s meaning (Heylighen 1999). Design theories are often intended to be general, but are not predictive as theories in science often are. Design processes describe design in terms of common activities that characterise designing at different levels of detail, scope and specificity. It should be noted that this is only one perspective—the design research community has not adopted a universally-agreed distinction between perspectives, theories and processes.
Design perspectives, theories and processes collectively paint a picture of design and provide useful vocabulary, best practices, and tools and methods for people interested in the topic.

Firstly, to give some examples of *design perspectives*, design has been studied from the perspective of rational decision making supported by mathematical tools to help evaluate alternatives, and also from the perspective of the ways designers think when they approach design tasks. These and other perspectives will be discussed in forthcoming sections.

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

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

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

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

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

- Abstract models convey theories and conceptual insights concerning the DDP. Such models have yielded important insights into design and development, and have inspired the creation of pragmatic approaches, but many of them do not directly offer guidance for practitioners.
- Procedural models convey best practices intended to guide real-world situations.
- Analytical models provide situation-specific insight, improvement, and/or support which is based on representing the details of a particular DDP instance.
Management science/operations research (MS/OR) models use mathematical or computational analysis of representative or synthetic cases to develop generally applicable insights into DDP issues.” (Wynn and Clarkson 2018, p.164)

In terms of scope, they define another three categories:

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

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

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

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

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

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

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

1.5 Overview of the next sections

The next sections provide an introduction to a selection of well-established design perspectives, theories and processes applicable when designing engineering systems. Section 2 will discuss what is meant by design in the broad sense, unveiling some of the theoretical foundations and influential perspectives on design. Perspectives and theories provide insights and means to view and approach design problems and their general nature makes them interesting for practicing and researching design, since “there’s nothing as practical as good theory” (Lewin 1951). In Section 3, we introduce design processes as a means to both understand and prescribe design and discuss how a selection of processes are relevant for design of engineering systems.

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

In Section 4 we discuss the utility of design perspectives, theories and processes when designing engineering systems by raising how some of the challenges that are commonly faced can be met. Section 5 summarises important points to take away from the chapter.
2 Theoretical perspectives on design

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

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

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

2.1 The scope of design

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

While everybody to some extent does design and can design, design is also a research discipline and a professional practice that can be studied. In fact, the study of design as a generic activity – as opposed to the study of some specific design domains – is a relatively recent addition to the academic canon. When the Open University in the UK launched a course in the late 1960s called “the man-made world” (The Open University 2020), this was a pioneering and influential effort in design education. The course was set out to teach design as a generic activity across different domains and highlighted the responsibility of designers for society and the environment. Mass distance education required a decoupling of design theory and design practice, where the theory needed to be made explicit and applicable to design in different domains and illustrated through examples in different domains. This work to identify what is generic about design processes across all different domains still continues (e.g. Daly 2009; Reymen et al. 2006). Less effort has been placed on understanding how design processes in different domains are different and why (Stacey et al. 2010).

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

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

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

The conceptualisation of design processes will be discussed in more detail in Section 3.

The term “design” has its origins in the Latin term designare meaning

1. indicate/designate/denote; 2. to mark; 3. point/mark/trace out, outline/describe.

From this comes the Italian word for drawing, disegno. In the 16th century Giorgio Vasari introduced painting, sculpture and architecture as the arti del disegno (Burioni 2012). Italian and other European languages like German maintained the strong link between design and form-giving, and have typically associated the term design with subjects that come from an art school tradition, such as product design, fashion design or graphic design. In German the term design is therefore focused on artistic aspects, while engineering systems design would be described as Entwicklung, i.e. development.

The English term design is broader and encompasses any type of plan or specification for building of objects or systems and the process of creating such a plan. Consequently the English term design is applied to many different areas, much as mechanical design, industrial design or sometimes even systems engineering.

In recent years, design or design thinking has also been adopted outside of traditional product design domains. The highly influential Cox Review of Creativity in Business (UK Government 2005), commissioned by the UK government, puts it like this: “Design is what links creativity and innovation. It shapes ideas to become practical and attractive propositions for users or customers. Design may be described as creativity deployed to a specific end.” This is based on definitions that “Creativity is the generation of new ideas – either new ways of looking at existing problems, or of seeing new opportunities, perhaps by exploiting emerging technologies or changes in markets” and “Innovation is the successful exploitation of new ideas. It is the process that carries them through to new products, new services, new ways of running the business or even new ways of doing business. This has moved design and creativity into the centre of public discourse in the UK and argued for supporting creative industry as one of the drivers of UK economy (Design Council 2018). The definition adopted for the creative industries as those industries which have their origin in individual creativity, skill and talent and which have a potential for wealth and job creation through the generation and exploitation of intellectual property” (DCMS 2001, p.4). They included not only traditional design fields such as architecture and artistic design domains such as product design, graphic design or fashion, but also the creation of cultural artefacts such as advertisement, media, music, visual arts and publishing. This included aspects of software design and IT, such as games design. This definition goes back to a study by Caves (2000), who investigated industry sectors where the participants were driven by a passion for what they do, and put up with a very uneven pay for similar tasks.
Overall the scope of design is wide, with a clear movement to embrace design as a problem-solving and solution seeking-approach for everyone. Recognising the commonalities and differences between different approaches can help to use them in a constructive way. In fact, engineering systems design combines many different aspects of design. The engineering challenges apparent when designing engineering systems require deep technological and scientific knowledge, as well as means to represent, manage and control the evolution of complex systems such as aircraft and their interactions with users, stakeholders and society.

2.2 Theory meeting the challenges of design

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

Renaissance books of mechanisms, as well as drawings and descriptions of machines, were systematically published and shared (Ferguson 1977). The first texts on engineering design can be found in the early 19th century, notably in the wake of setting-up the first technical universities, e.g. Ferdinand Redtenbacher (1848), who pointed out that machine-related knowledge alone is not sufficient—a talent for invention and an understanding of the mechanical process the machine must serve are also required for effective design. A modern engineering systems designer would recognise technical knowledge, creativity, and an understanding of purpose and context as the constituent elements of successful engineering design. Since the Second World War engineering design has become more structured and increasingly more based on mathematical and computational analysis (Ferguson, 1992). Consequently, engineering design and its methods have today become very strongly influenced by the capabilities of the computational tools that support it.

In the middle of the 20th century architectural design was a major driver of design theory development. For example, Alexander (1977) developed the idea of patterns in design, representing similar solutions at a fairly high level of abstraction. Computer Science as a discipline developed some of its own theoretical foundations for design, while drawing on general design theory. For example, the idea of software patterns built on Alexander’s ideas (Gamma et al. 1994). More recently many of the different design research communities have fragmented and have developed their own vocabularies. Bringing the concepts, ideas, models and methods of these different communities together is one of the challenges of future engineering systems design. This is much-needed to meet the expectations in design of engineering systems, in which the interaction with the system context becomes an essential issue to be considered during design.

2.3 Perspectives on designing for engineering systems

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

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

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

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

2.3.2 Design as rational problem solving

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

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

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

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

- Naming: recognising an element as a meaningful entity and giving it is name at a suitable level of abstraction, e.g. calling a connected line a “square” or a “swimming pool”
- Framing: in which different named objects are pulled together into a more general problem frame
- Moving: in which the design is advanced within the current frame
- Reflecting, in which the design is evaluated before the next cycle begins.

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

2.3.4 Design as addressing wicked problems

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

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

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

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

2.3.5 Design as a unique mode of thinking

Cross (2006) carried out many interviews with famous designers to identify characteristics of their way of thinking, which he concludes goes beyond what ordinary designers or lay people would engage in. He termed this designerly thinking, taking a cognitive approach to how excellent design practitioners do design. This work represents some of the academic underpinning of the wider design thinking movement that is described in Section 2.3.6.

Cross identified the following characteristics of designerly thinking:

- **Rhetorical and exploratory:** A designer explores and might break new ground and therefore might need to persuade colleagues or clients of the merits of the new design. To illustrate the rhetorical nature of design Cross cites the architect Denys Lasdun (1965): “Our job is to give the client ... not what he wants, but what he never dreamed he wanted; and when he gets it, he recognizes it as something he wanted all the time.”

- **Emergent:** Design problems are ill-defined, and as already discussed, designers reframe the problems many times throughout the design process. Cross quotes the architect Richard MacCormac (1976): “I don’t think you can design anything just by absorbing information and then hoping to synthesise it into a solution. What you need to know about the problem only becomes apparent as you’re trying to solve it”.

- **Intuitive and abductive:** Designers build conclusions based on partial information. Rather than having a full understanding of a problem, they lead formats to proposing a new solution. They see links between ideas that other would not. See e.g. (Dorst 2011).

- **Reflective:** Designers engage, as argued by Schön into a dialogue with external media.
• Ambiguous and adventurous: Designers can live with uncertainty and push the limits of what has been done so far or what would be expected of them. This also can entail a certain personal risk as they put their judgement at stake.

2.3.6 Design thinking as a universal approach

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

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

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

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

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

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

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

2.3.8 Design as a holistic activity beyond the artefact

A Product-Service System (PSS) recognises that the value of an engineering system typically is associated to how well it performs in use, when provided as a service. Product-Service Systems equally acknowledge that the service provided depends on the characteristics of the product or system that enable service provision. Baines et al (2007) provides a summary of PSS concepts, that all share the central theme that a PSS is an integrated combination of products and services. Designing a PSS solution require both services and the physical artefact to be designed together with the business design.

Early definitions of PSS emphasised the environmental advantages of combining products and services together such as Mont (2004), since the PSS model incentivises business to be more resource aware and enables shared use of (sub)systems across PSSs. According to Mont (2004), “PSS is a system of products, services, supporting networks and supporting infrastructure that is designed to be competitive, satisfy customers’ needs and have a lower environmental impact than traditional business models”. Another definition is offered by Tukker and Tischner (2017) who defined first the product service as “a value proposition that consists of a mix of tangible and intangible service design and combined so that they jointly are capable of fulfilling final customer needs” and second, the PSS as the
“product-service including the (value) net-work, (technological) infrastructure and governance structure (or revenue model) that produces a product service”.

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

2.3.9 Section summary

The eight different perspectives of design that have been described in subsections 2.3.1-2.3.8 have arisen, in part, because researchers have focused on different aspects of design problems. Figure 4 illustrates a possible mapping between these design perspectives and the elements of engineering systems design that were presented in Figure 2. In particular, Design as decision-making (Section 2.3.1) arose from trying to select solution alternatives, such as the selection of a suitable compressor and turbine blade geometry, where objective and measurable criteria apply. Design as rational problem solving (Section 2.3.2) emphasises a broader problem, but one with goals and structure. Design as reflective practise (Section 2.3.3) and design as a unique mode of thinking (Section 2.3.5) both highlight the importance of holistic and tacit thinking in design, that goes beyond what can be mathematically modelled. For example, this is highly relevant when describing early conceptual design before equations are available. Design addressed as a wicked problem (Section 2.3.4) highlights that in many design problems the solution ought to work first time. For example, an entire airport can be prototyped and – as the infamous new airport in Berlin illustrates – getting it wrong is highly costly (Fiedler and Wendler 2016). Recently these ideas have been broadened to designing the product and the processes in conjunction. What all these conceptualisations have in common is that they focus on the designer as a trained professional. The design thinking as a universal approach (Section 2.3.6) brings the user explicitly into a co-creative design process. In participatory approaches (Section 2.3.7) the user is the expert of its own needs, who can give feedback to the designer, whereas design thinking focuses on appreciating needs and generating innovative solutions. Both these focus on user experience and are less applicable for constrained safety critical applications. For such design, e.g. sizing and optimisation of reliable and efficient machinery rational design strategies and decision-based design are more applicable. Complex design involving life cycle aspects and sustainability performance are candidates for design beyond the artefact (Section 2.3.8).
2.4 Design theories and engineering systems design

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

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

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

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

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

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

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

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

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

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

According to FBS, designs are generated through the iterative application of eight processes to these variables: Formulation, Synthesis, Analysis, Evaluation, Documentation and Reformulation of the function, structure and the behaviour, see Figure 6. Gero and Kannengiesser (2004) develop this further to reflect the situatedness of human cognition, and applied to processes (Gero et al. 2007). While the definition of function in FBS is intuitive to native speakers to English, other notions of functions with associated theoretical frameworks exist (see Vermaas, 2013; Crilly 2010).

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

Fourthly, C-K theory (Hatchuel and Weil 2009) claims to be an unified and formal design theory, that argues that design can be modelled as the interplay between two interdependent spaces: the space of knowledge (K), which contains the proposition that are validated or assumed to be true and the space of concepts (C), which are (yet) undecidable. The design process generates both knowledge and concepts and can be seen as moving between these spaces:
- K to C (disjunction): a concept is proposed based on knowledge
- C to C (expansion), a concept gives rise to a concept
- C to K (conjunction), a concept becomes established knowledge
- K to K (expansion), new knowledge is derived from existing knowledge.

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

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

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

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

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

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

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

3 Design processes

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

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

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

The discussion of process models in this section is organised broadly around the classification of such models presented by Wynn and Clarkson (2018). These authors write that process models consider the design and development process at three levels, namely the micro-level, meso-level and macro-level. The distinction between these levels focuses on the scope of the process considered by a particular model, which is not necessarily the same as the number of people involved, the timeframe or the scale of the design situation. To recap from Section 1, micro-level models emphasise individual activities and their immediate contexts. Meso-level models concern end-to-end flows of work related to the progression of a design. Macro-level models concern the interface between the design process and its context, including project structures.

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

There are numerous process models of each type and at each level of scope. Noting that the focus of this section is on engineering systems design, the framework presented by Wynn and Clarkson (2018) is reinterpreted for this context in Figure 7. The figure indicates how the design theories discussed in Section 2.4 fall into the abstract category of the aforementioned framework, the process models to
be discussed in this section fall into the procedural category, while the perspectives on design discussed in Section 2.3 are relevant to all types and scope of process model. The next subsections revisit some points from Wynn and Clarkson (2018) with consideration to the engineering systems design context.

3.1 Micro-level procedural design process models

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

A strategy that is commonly articulated in micro-level process models is that designers should follow a series of cycles, on each cycle working through the issues systematically and trying to avoid jumping to solutions based on their preconceptions. Evbuomwan et al. (1996) review work from the 1960s incorporating this recommendation, including Marples (1961), Jones (1963) and Archer (1965). Each of these authors recommends that design should follow the three main steps of analysis, synthesis, and evaluation. During analysis, the designer is expected to focus on a particular design sub-problem and then work to structure it, yielding a set of objectives. During synthesis, they should generate multiple solutions. Evaluation involves the critical appraisal of those solutions against the objectives resulting from the first step, allowing the best design to be selected and yielding insight for iterative improvement. Design process models incorporating this strategy are often described as problem oriented because they stipulate starting from analysis of the problem to be solved on each design iteration (Wynn and Clarkson 2005). They suggest that within an iterative cycle, designers can...

Figure 7 Theories, perspectives and processes on engineering systems design classified according to the framework of Wynn and Clarkson (2018). Each approach shown on the right hand side is discussed in this chapter.
formulate problem statements that do not presuppose a solution, which is desirable to help combine systematic reasoning with creative insights.

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

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

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

3.2 Meso-level procedural models

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

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

Other meso-level models present the engineering design process as a series of stages, each of which creates additional information to further concretise and detail the emerging design. In the mechanical design context this stage-based form is exemplified in the early work of French (1999), originally published in 1971. Later models focusing on mechanical design, notably in the work of Hubka and Eder (1996) and Pahl et al. (2007), incorporate detailed lists of working steps to be followed to complete each stage. These models define how to create the specific forms of information that constitute a mechanical design, progressing from abstract to concrete and so that each stage establishes the objectives and, also, the constraints for the next. These stage-based models typically show feedback loops between the stages. These indicate that design rework might occur at any point; they also indicate that learning can occur between projects and across product generations. In the mechanical design context, process models of this type are strongly influenced by theories of the information structures that define a mechanical system design and its operation—such as the Theory of Technical Systems (Hubka 1988, Hubka and Eder 2012) that was discussed in the Design Theories section of this chapter. Stage-based models also appear outside the mechanical design context.

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

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

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

3.3 Macro-level process models

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

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

Other processes in this category aim to mitigate the risk of costly iterations that cross stages of the development process. One such model commonly used in practice is the stage-gate process (Cooper 1990), which emphasises the use of formal, structured reviews to ensure a project has reached sufficient maturity before allowing it to proceed from one stage to the next. Another is the Systems Engineering Vee model which graphically depicts how a complex design is or should be decomposed into subsystems which are developed individually, and then integrated, verified, and validated at each level as they are combined back up the hierarchy of subsystems (Forsberg et al. 2005; VDI2206 2004). Key concerns in classical systems engineering include ensuring and documenting the definition, flowdown and control of requirements and interface definitions, in order to avoid uncontrolled changes and the consequent rework. A third model that has gained attention is set-based concurrent engineering (SBCE), which advocates controlled reduction of technical uncertainties through a focus on up-front learning about whether the emerging design is feasible. The guiding principle is that concepts need to be proven feasible from the start to avoid large-scale rework, and also to allow more standardised work later in the design process (Kennedy et al. 2014). SBCE proposes that this should be approached by developing and maintaining several workable designs for each subsystem, and progressively discarding those options that are found to be infeasible or found to generate integration difficulties as the design moves forward. This is a significant departure from
the more common practice of creating one design for each subsystem and iterating until they can all
work together but, although offering many advantages, has proven challenging to implement in many
contexts. SBCE also suggests that target specifications should, in the ideal case, be allowed to evolve
within limits until it is established that the design will be able to meet them.

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

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

3.4 Section summary

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

Meso-level processes capture and communicate a shared understanding of central concepts, e.g. how
design solutions are matured through the activities undertaken and when particular reviews should
take place. Continuing on the requirements example, meso-level processes are helpful when
organising and decomposing the requirements phrased using micro-level processes.
As was indicated at the start of this chapter, engineering systems design typically involves many people and many organisations requiring careful coordination to converge to a consistent result. Macro-level processes provide overall approaches to frame and bound a large-scope problem and facilitate both creative, synthesis activities to utilise new technologies, possibly from new domains into the process. By helping to coordinate the people and activities involved in design on a large scale, macro level processes can be useful to reduce wasted effort in the design process and allow designers to focus effort and time on the development of robust and resilient engineering systems.

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

4 Application of design perspectives, theories and processes to practical case examples

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

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

The different perspectives on design help designers to appreciate particular aspects of design, as depicted in Figure 3. Any complex design situation involves a multitude of challenges that need to be addressed, and selecting appropriate perspectives for the given situation can help to find appropriate methodological support. For example, airport and aircraft design, which this section uses to explain how design relates to different dimensions in engineering systems design, are prime examples of wicked problems, see Section 2.3.4, and hence approaches to support such problems are relevant.

Figure 8 builds further on Figure 2 to illustrate that engineering systems design is subject to many challenges arising from the systems complexity itself (large aircrafts have millions of parts and millions of lines of software code) and the long and varied use of the product, but also the organisational and societal context in which the products needs to operate. Intervening in such systems necessitates that designers address design problems across multiple dimensions. De Weck et al (2011) provide a set of engineering systems terms and definitions that can serve as a guide to many of the relevant topics. In the following, we briefly discuss a subset of the dimensions depicted in Figure 8, which will help illustrate the role perspective, theories and processes can play in engineering systems design practice.
Firstly, as already stated, for each intervention into a complex engineering system, the designers face a number of challenges and need to operate on multiple dimensions. The colour scheme of Figure 8 reflects the three main dimensions of the PSI framework discussed earlier (Reich and Subrahmanian 2020). In particular, the blue dimensions relate to what is being designed, the green dimensions relate to the stakeholders in design and the orange dimension relates to the institutional aspects, i.e. the economic, managerial, organisational and political aspects impacting design. As pointed out in the earlier section, engineering design theories, perspectives and processes have traditionally paid little attention to the institutional space. The addressing of this gap is a current trend in design theory development.

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

Thirdly, the nature of innovation plays a decisive role for selecting suitable design approaches. Disruptive system innovation, such as aerospace replacing energy transformation principles (electrification, hydrogen power, hybrid technologies), is significantly different from evolutionary development. Simply comparing different type of solutions may be difficult unless system level performance, behaviour and functionality can be compared on equal basis. Here, design theories such as axiomatic design (Suh, 1990), C K theory (Hatchuel and Weil, B., 2009) or Function modelling (Gero (1990) provide frameworks to compare disparate solutions. In addition, disruptive innovation entire systems require multiple systems and people to change their way of interacting with the systems. Design Thinking perspectives have been found useful to improve communication between different type of competences and stakeholders and promote ideation.
Fourthly, the *application context* of engineering systems design accounts for the situations the system is being designed for. Perspectives, theories and processes need to be adapted to the particular situation, or context. Generic and typically abstract, design theories can be useful to design health systems, aerospace systems, communication systems and more, yet the contextual terminology, the technologies used to design and realise the systems, material and so forth are different. There are few recipes to be found in design theories and perspectives, but there are many valuable insights on how to make the systems “designable”. Design theories origin from one domain, e.g. software, are at present influencing design of multi-technological systems, such as the agile manifesto. Also here, agile principles need to be adapted to the particular challenges for the new context.

For example, this illustrates the interplay between the functions that a system needs to carry out and the structure that it has. A large existing structure might have to carry out new functions or a changed structure needs to maintain existing functions. To analyse this different theories discusses in section 2.2., such as FBS (Gero and Kannengieser, 2004) might provide conceptual clarity between the purpose of the system (function), the elements that it has (structure) and the resulting behaviour. Evident from social occasion, such as the Covid-19 crisis, completely altered conditions for flight transport systems. The ability to adapt and design for the unexpected has a big impact, where designers may benefit from building on modular systems, where design theory provide means to de-compose and organise complex systems. For example axiomatic design (Suh, 2001) advocate a clear mapping between components and functions, so that it one function changes are remain relatively unaffected.

Fifthly, a related dimension is that of *Uncertainty*. Design by definition is made in advance of the realisation of the systems and products. At the start of a design initiative, typically the both the the knowledge of the use conditions and the forthcoming design solutions are vague, incomplete and imprecise. Both design theories and processes have been developed partially with the objective of reducing the uncertainty of designs by seeking knowledge that allow uncertainty to reduce. The concept of wicked problems by Rittel et al (1973) (see Section 2.3.4) is a good source of inspiration. As designs mature, increased use of engineering modelling and simulation as well as prototyping can be effective. Many uncertainties arise because the use context has not been well understood and explored, which can be potentially be alleviated through participatory design approaches (see section 2.3.7).

Sixthly, in terms of *System Dimensions*, elements of engineering systems are often highly optimised technical systems, such as subsystems of aircraft. The overall design problem is decomposed into smaller and more manageable problems, see section 2.3.2. Even though the problems cannot be fully decomposed in theory, they have to be decomposed and integrated later in practice to manage to division of labour between different designers and make the tasks of an individual more manageable. This applies in particular to engineering systems design which typically addresses large problems at multiple levels of hierarchy, as suggested by Figure 1. In this decomposition some design theories and processes might be more applicable than others to particular aspects of the design. For example, aircraft designers might take a participatory approach, see section 2.3.7, to designing the overhead luggage bins, because the passengers have to use them as fast and smoothly as possible, but the users of the aircraft are not particularly relevant to the design of the hydraulic system. The hydraulic system can be treated using mathematical decision based methods, see section 2.3.1. A technical system cannot be designed in the absence of understanding and to some extent designing the processes and products it needs to interact with, so that PSS approaches (section 2.3.8) might be useful.

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

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

5 Conclusions

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

The multifaceted nature of design allows for a range of useful perspectives on design (discussed in Section 2) that help engineering system developers to address problems encountered in their work. For instance, in situations where they need to organise their complex, typically wicked (Rittel and Webber 1973) problems, Simon (Simon, 1996) discusses how to carve out more concrete problem definitions using the perspective of bounded rationality and Schön (Schön and Wiggins 1992) elaborated further on cycling between the abstract and concrete as a means to progress in design. To think and act as a designer has become the cornerstone for approaches that have become popular as universal problem solving activities – typically engaging a team of diverse skills in seeking solutions. At present, thought leaders in design research seek to develop design perspectives that extend way beyond artefacts and concrete systems to incorporate issues relevant to the larger-scale socio-technical engineering systems context. As such, these perspectives of design help to nuance and view seemingly overwhelming problems in new light.

Formal theories of design (as discussed in Section 2) have a higher ambition on formalism and seek to understand design and, in some cases aim to robustly predict the outcome of design activities. Early theories assumed a well-defined problem, and started with the artefact being designed, such as Theory of Technical Systems (Hubka and Eder 1988) or Andreasen (1980), while others take a more abstract view on design, such as Suh (1990) with Axiomatic Design, Gero and Kannengiesser (2004) with their FBS ontology and framework, and (Hatchuel and Weil, B. 2009) with their C-K theory. Current theoretical developments seek to take a wider systemic view of design (Subrahmanian et al. 2020). There is a trade-off between general applicability of theories and the effort required to adapt them to a particular context.

Perhaps more widely applied are the processes (as discussed in Section 3) that offer concrete design steps and sequences such as Pahl et al (2007) or Ulrich and Eppinger (2015), while other processes offer high-level frameworks to help manage complex design projects. Examples of the latter are Concurrent Engineering (e.g., Prasad 1996), The Toyota System (e.g. Liker and Morgan 2006) or the Agile Manifesto (Beck et al. 2001) and their derivatives. These are highly relevant to engineering systems designers due to the approaches’ proven utility for large scale and complex problems. One of their drawbacks is that (in common with design perspectives and theories) they need to be adapted to each specific context.
Design theories and design processes that have been tested and validated through research can be of great value when addressing complex problems for Engineering Systems Design. Many of the problems that frequently appear in development situations can be viewed as design problems, whether they relate to formulating the problem in a way that they can be solved, or determining how to evaluate whether a proposed solution actually meets expectations and requirements. Design theories have evolved over decades of practical development and bring well-structured approaches to help in addressing complex problems. They are well worth the investment of time and effort to appreciate them! In doing so, it is essential to recognise that design has simultaneously a technical dimension and a social dimension, including human, institutional, and political factors affecting the decision making process. For the engineering systems addressed in this book, successful design needs to acknowledge both factors in a balanced way, where a balance between rationality and situation awareness for decision making need to be attended to.

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