TITLE: Engineering system design goals and stakeholder needs

A. AUTHORS

Alison McKay (corresponding)
University of Leeds
Leeds, UK
a.mckay@leeds.ac.uk
ORCID: 0000-0002-8187-4759

Ole Broberg
DTU-Technical University of Denmark
Kongens Lyngby, Denmark
obro@dtu.dk
ORCID: 0000-0002-9511-9439

Mark A. Robinson
University of Leeds
Leeds, UK
m.robinson@lubs.leeds.ac.uk
ORCID: 0000-0001-5535-8737

B. ABSTRACT

The engineering systems covered by this book are complex socio-technical systems. Their complexity results from two key characteristics: the technical complexity in their physical manifestations and the elaborate processes, usually operated by people, needed to realise, use, and support such systems through life. Although engineering design tends to focus on technical aspects of these physical manifestations, it is the delivery of the associated processes, e.g., realisation, use, and through-life support, which create value (or frustration) for stakeholders. For this reason, understanding the needs of stakeholders who participate in these processes is critical to the success of the overall system. In this chapter, we consider how one might go about understanding stakeholder needs and formulating engineering system design goals. Three overarching approaches to the design of engineering systems (user-driven design, designer-driven design and systems engineering) are introduced, and examples of their application to practical design work are provided through three design case studies. One case study relates to the design of a surgical device, the second to the design of a knowledge management system and the third considers how the approaches introduced in this chapter might be applied when designing in response to sustainable development goals.

C. KEYWORDS

Designer-driven design, design case studies, engineering systems, requirements management, stakeholder needs, systems design, user-driven design

D. INTRODUCTION

The complexity of socio-technical systems, such as the engineering systems considered in this book, arises from two sources:

(1) the technical complexity in their physical manifestations, and
(2) the processes, usually operated by people, often in organisational contexts, needed to realise, use, and support these systems through their lifecycles and decommissioning.

Engineering design processes typically begin with a collection of product or system design goals that are translated into, and ideally quantified as, design requirements. These requirements then drive the development and realisation processes that, in turn, govern the final product or system that is delivered to customers and other stakeholders who enact the product's lifecycle processes. In this way, for large, complex and long-lived engineered products, what begins as a product design project becomes a large-scale socio-technical systems design project.

The focus of this chapter lies in the journey from a future product's lifecycle processes, and so the needs of people and organisations who form the large-scale socio-technical systems that deliver these processes, to design goals. For large, complex products, this journey is challenging to manage and deliver because the products, and so their lifecycle processes and systems, are often parts of solutions to wider, so-called, "wicked" problems (Farrell and Hooker, 2013). Farrell and Hooker define three characteristics of wicked problems that make finding solutions, and associated design goals, more challenging than for more simple design problems:

(1) **Finitude:** no single individual can establish a full understanding of the whole problem;
(2) **Complexity:** the problems include a number of highly interconnected issues, making it impossible to relate actions with consequences;
(3) **Normativity**: the problems are parts of [socio-technical] systems whose operations are governed by social and cultural norms that influence both the feasibility and adoption of proposed solutions.

Thus, there are also three associated problems in designing solutions to such wicked problems:

(1) the problem itself is not well understood;
(2) the interconnected nature of the problem, including stakeholders with multiple allegiances, and so needs, goals and aspirations, means that it is not always possible to predict the wider impact of proposed solutions; and
(3) the overall behaviour of the solution is governed by human and organisational behaviours as well as characteristics of the solution itself.

In this chapter, we introduce a range of methods that are used to navigate this journey and so understand stakeholder needs in ways that support the formulation of system design goals and accommodate the ambiguities and contradictions that typify design goals for open-ended design problems. We begin with a review of current state-of-the art approaches to understanding design goals and stakeholder needs. There is no clear step-by-step process for doing this, so this section focusses on three kinds of design process that explore stakeholder needs and design goals in different ways. The first two, in line with Vermaas et al. (2014), distinguish between user- and designer-driven methods and the third covers approaches to the design of wider systems:

(1) User driven design processes, such as participatory design and user-centred design, where methods used aim to elicit needs and requirements directly from users and other stakeholders;
(2) Designer-driven processes, such as parts of IDEO's design thinking process, design ethnography, and Vision in Product Design, which are designer rather than user led and where the focus is on the use of theories and methods from the social sciences to understand and predict future human and organisational behaviours and so future stakeholder needs; and
(3) Systems engineering and three different ways to look at the systems of which both lifecycle processes and stakeholders are critical parts.

We conclude this section with a framework for selecting appropriate approaches. This is followed by three case studies that are used to provide examples of how these approaches can be applied in the design of engineering systems.

E. MAIN TEXT

1 State of the art in understanding stakeholder needs and formulating design goals

Design goals are important because they drive both creative aspects of design processes and the evaluation of design solutions. More widely, using goal-driven, as opposed to solution-driven, design processes is critical to delivering value to stakeholders. For example, the UK's Crossrail project had cost overruns of circa £600 million (anon, 2018) and lessons-learnt reports include recommendations for the management of quality in supply chains and for the use of goal-oriented development processes (Elliot, 2018). Design is a key mechanism in delivering quality, especially for engineering systems, where quality covers the reliable delivery of required functionalities to users for which a prerequisite is the effective and efficient operation of the socio-technical systems that deliver through-life processes such as operation and maintenance.

Given that engineering systems are typically designed, produced, and supported through life by networks of organisations, the supply network (which might be better termed the "lifecycle network") is a critical starting point for identifying stakeholders and so their needs and goals.

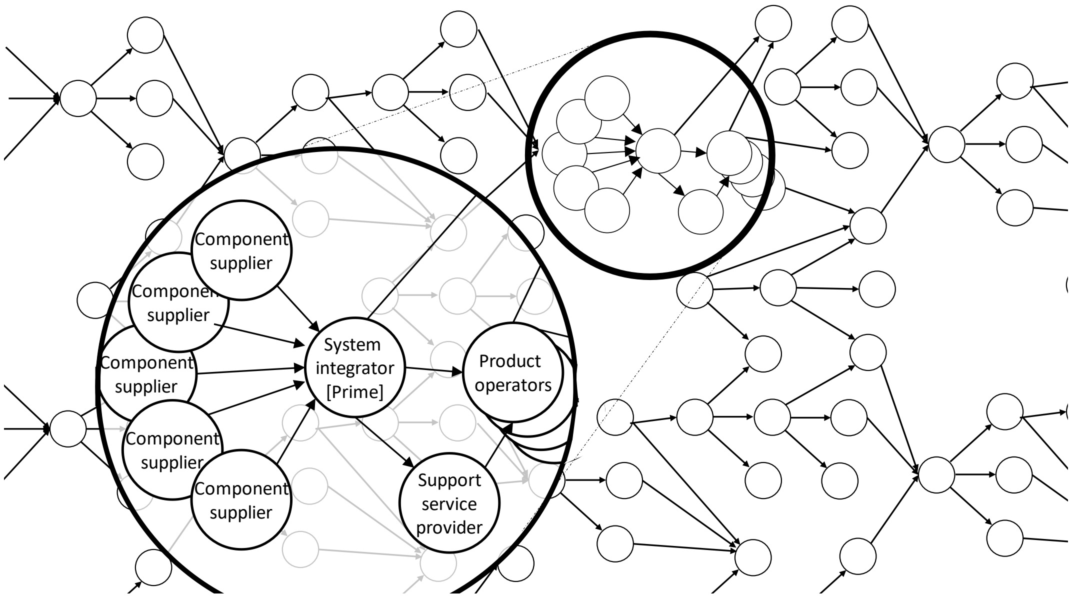

Figure 1: Lifecycle supply chain schematic (nodes represent organisations, and arrows represent flows of goods, information, and/or money between them)

Figure 1 shows a schematic of the kind of organisational network, and so socio-technical system, needed to support the lifecycle of a large, complex, engineered product. The detail balloon expands just one aspect of this network, a prime contractor, its Tier 1 suppliers, and the operators and support service providers of the product in the design and development part of the product lifecycle. Even from this small fragment, the complexities of these networks are apparent (McKay et al., 2013, Kundu et al., 2012). In general, the figure highlights three key factors in the formulation of design goals:

(1) the range of organisations and relationships between them in life-cycle support networks creates complexities that are difficult or impossible to untangle;
(2) it is infeasible for any one organisation to understand and manage the design goals and needs of the whole network; and
(3) no single organisation is in a position to control the operation of the entire network.

Fine (1999) discusses similar issues in his book on 3D concurrent engineering, covering the concurrent design of products, processes, and supply networks. For (1) and (2), he suggests identifying an organisation to act as a focal-point (e.g., the design organisation) and then considering the needs and goals of organisations two-up and two-down in the network (although he does also provide examples of where such an approach failed to identify supply chain risks). For the identification of design goals, two-up the chain covers the goals of the direct customers of the focal company and their customers (the customers' customers). Two-down the chain implies suppliers and suppliers' suppliers whom, if looking at a lifecycle support network, could include organisations such as maintenance service suppliers and requirements for lifecycle support processes who, in design, take the role of customers. The needs of these organisations can be grouped together as *customer needs*. Two other common groups of requirement influence the needs of each organisation in the network. First, each organisation in the network has its own *business requirements*, typically to be financially and, increasingly, environmentally and socially sustainable, but also linked to its own strategic goals. Second, for engineered systems, there are usually regulators who provide *regulatory requirements*.

In what follows in this chapter, we group current practice in understanding stakeholder needs and formulating design goals into three categories. The first two categories cover approaches that focus on the product being designed (which may be a physical product or an associated service). In Section 1.1, we introduce participatory design and user-centred design-based methods where users and other stakeholders are actively involved in the design process. The second category covers approaches where, for whatever reason, users and other stakeholders are unable to provide a full enough picture of future needs. In these cases, designer-driven approaches, introduced in Section 1.2, are used to incorporate social science perspectives and provide insights into future needs and so current design goals. The final category (in Section 1.3) covers systems-based approaches, where the emphasis is on viewing both problem domains and solutions as holistic systems that are connected to parts of other, often wider, systems and situations. Having introduced these approaches, we illustrate their application to three case studies, in Section 2, and we conclude, in Section 3, by considering future avenues for development in both practice and research.

1.1 User-driven design approaches

The vast majority of design processes emphasise the importance of understanding user and other stakeholder needs and requirements. Participatory and user-centred design are two approaches that can be used to achieve this, by bringing users and other stakeholders into the design process. Both approaches can be used in a given design activity but their foci differ: participatory design (Section 1.1.2) builds understanding of stakeholders' needs by including the voices of these people and their representatives in the process, whereas user-centred design (Section 1.1.1) focusses on the capabilities of target users to inform design goals. However, the two approaches are not necessarily distinct and can be used in complementary ways by human factors practitioners, for instance (Nemeth, 2004), where users' affective reactions are also sometimes considered in accordance with Kansai engineering approaches (Bahn et al., 2009).

1.1.1 User-centred design

User-Centred Design (often used synonymously with Inclusive Design or Human-Centred Design) is about designing *for* users. The concept of user-centred design (UCD) became widely popular after the publication of a book by Donald Norman in 1986 (Norman, 1986), and the Inclusive Design toolkit (Roger Coleman (Editor), 2017) provides practical methods to ensure that the goals of user-centred design, to make products which have a high usability, are met. The approach is common in the design industry because it leads to increased product usefulness and usability. The International Standard on Human-Centred Design (ISO 9241-210:2019) provides a number of principles that human-centred approaches should follow:

(1) the design is based upon an explicit understanding of users, tasks and environments;
(2) users are involved throughout design and development;
(3) the design is driven and refined by user-centred evaluation;
(4) the process is iterative;
(5) the design addresses the whole user experience; and
(6) the design team includes multidisciplinary skills and perspectives.

When developing a human-centred system, product or service, four linked design activities take place during the design process: (1) Understand and specify the context of use; (2) Specify the user requirements; (3) Produce design solutions to meet these requirements; and (4) Evaluate the design against requirements. In this chapter, we are focussing primarily on the first two activities.

Understanding the context of use includes identifying the relevant user groups and other stakeholder groups, key characteristics of these groups, their goals and tasks of the overall system, and the environments of use for the proposed system. Methods may include user group profiling and the development of as-is scenarios and personas, as well as participatory design and soft systems approaches. In a system design project, specifying user requirements is a major activity that includes the identification of user needs and specification of functional and other requirements for the system. These can include requirements for organizational changes and revised work styles. In such cases, the development process should involve organisational stakeholders with the aim of optimising both organisational and technical systems. Considering the context of use, the specification of user requirements must (according to ISO 9241-210) include:

(1) the intended context of use;
(2) requirements derived from user needs and the context of use;
(3) requirements arising from relevant ergonomics and user interface knowledge;
(4) usability requirements and objectives; and
(5) requirements derived from organisational requirements that directly affect the user.

The ISO standard further points to potential conflicts between user requirements that should be resolved, ideally achieved by involving the relevant stakeholders.

1.1.2 Participatory design

Participatory design extends user-centred design's philosophy of designing *for* users, to include a wider range of stakeholders, which leads to a key strength of participatory design: its potential to generate design solutions while also involving relevant stakeholders in the design process (Drain et al., 2018). The idea is to bring in real-world users as key stakeholders during the entire design process. It is about user involvement in design projects and design teams. Participatory design is about changing users' roles from being merely informants to being legitimate and acknowledged participants in the design process (Robertson and Simonsen, 2018). The participatory design approach has developed widely into many different types of design process. The underlying idea is that the active involvement of stakeholders helps ensure that the design result meets users' needs and is desirable, usable and affordable. Stakeholders, whether putative, potential or future, are invited to cooperate with designers, researchers and developers during the design process. This includes the initial phase where the problem is explored, and problem definition and design goals are established.

Participatory design is also about users and (system) developers learning together about possible and useful technical solutions. It focusses on mutual learning processes. A socio-technical approach and understanding practice are fundamental to participatory design. The term 'practice' refers to what people really do in contrast to that envisioned or prescribed in workflow diagrams, for example, and other representations of work and other activities. For example, deep insight into current work practices is emphasised as a starting point for developing and understanding future practice in new or redesigned work-related systems (Robertson and Simonsen, 2018).

A number of methods, tools and techniques have been developed to support participatory design. Typically, the participation takes place in workshops with designers, users and other stakeholders using techniques such as mock-ups, scenarios, prototypes and various types of design game. Such tangible artefacts enable prototyping of and design experiments with selected elements of envisioned systems or technologies prior to their development and implementation. Design games were introduced in the participatory design area as a means for designers to involve people in design processes (Brandt et al., 2008, Brandt, 2006). Design games help organise collaboration between people with different competencies and interests. Brandt et al. (2008) focus on explorative design games as a way to organise a free space of exploration in collaborative design. They point to board games as a class of participatory design games that have the following features:

(1) a diverse group of players are gathered around a collaborative activity guided by simple and explicit rules, assigned roles and supported by pre-defined gaming materials;
(2) the gaming materials typically point to either or both existing practices and future possibilities;
(3) the games are played within a confined and shared temporal and spatial setting often removed from the players' everyday contexts;
(4) the purpose of the game is to establish and explore novel configurations of the gaming materials and the present and future practices to which these materials point; and
(5) at the end of the game, the players will have produced representations of one or more possible design options (Brandt et al., 2008).

There is a growing number of methods for participatory design of large-scale socio-technical systems. For example, Hughes et al. (2017) have introduced a systems scenario tool and applied it to designing the future of telehealth in UK, and Jun et al. (2018) demonstrated a participatory design approach to design for safer integrated medicine management. Both include workshops with representatives of many stakeholders, and included identifying and prioritising problems. Systems visualisation in the form of models and diagrams and using tangible materials in workshops are common techniques for enabling the participation of system stakeholders. Finally, Clegg et al. (2017) proposed an approach for predicting malfunctions in complex socio-technical systems, enabling them to be mitigated or prevented proactively, thereby applying organisational psychology as a design science.

1.2 Designer-driven design processes

Participatory design methods balance politically grounded ideology with practically driven design priorities to create effective solutions, while empowering involved stakeholders to have increased ownership over the final design (Drain et al. 2018). Key benefits of such, user-driven, approaches to design lie in the fact that, as a rule of thumb and although they often have difficulty articulating them, users or their representatives know what they do and don’t want and need. So asking them, and creating situations where they can express their needs and wants, is an effective way to elicit them. However, what happens if the users are inaccessible (for example in hard-to-reach communities) or if the design is for future needs and wants in the longer term, where today’s users are unlikely to know what they’ll want or need? Or, where the goal of the design is to deliver wider value? For example, to societal systems as a whole as opposed to individual users alone, though they may, of course, also benefit on multiple levels (Tromp & Hekkert, 2019). And, what if we do not know who tomorrow’s users are yet, and situations where there are high degrees of uncertainty related to policy decisions and other factors (social and technical) that will affect future users’ needs and wants? Designing for these situations requires wider perspectives and the envisioning of future scenarios that inform design goals (McKay et al. 2008). Designing in these contexts demands wider systems perspectives, such as those provided through soft and socio-technical systems based approaches (see Section 1.3), which feed information to the designer-driven approaches, based in the social sciences. Before moving on to system approaches, however, here we introduce three designer-driven approaches that are widely used to inform understanding of design goals and stakeholder needs. In Section 1.2.1 we introduce design thinking as a process for addressing wicked problems which emphasises understanding stakeholder needs. Following this, in Section 1.2.2, we introduce a particular method from the social sciences, design ethnography, which is used in design thinking processes and more widely, as a way of building insights into stakeholder needs and design goals. Finally, in Section 1.2.3, we introduce Vision in Product Design as a means of envisioning future design goals and stakeholder needs.

1.2.1 Design thinking

Design thinking is a widely used process that encourages a focus on user and other stakeholder needs. Stanford University's d-school has led the development of educational programmes on design thinking (Lewrick et al., 2018, Mabogunje et al., 2016) and perhaps its most well known proponent is the global design company, IDEO, who provide a brief history of the development of design thinking (IDEO, 2020a; Brown, 2009). Design thinking processes typically integrate designer- and user-driven approaches along with wider, systems approaches that are introduced in the next section. Key features of design thinking are the cycles of divergent and convergent thinking that it encourages and its aspiration to create solutions that are desirable (i.e., solutions that users want), economically viable (i.e., solutions that users can afford to acquire and use) and technologically feasible (IDEO, 2020b). The design thinking process itself includes iterative cycles of three core activities, ideation, inspiration and implementation (IDEO, 2020b). Implementation in each cycle is achieved through the creation of design prototypes. Harrison et al. (2015) explain how the design prototyping process helps uncover stakeholder needs and design goals.

Before moving on, we expand a little of what being technologically feasible means for engineering designers because of its relevance to both design thinking and systems approaches. In essence, it means that solutions can be implemented because the technologies they encapsulate are available and at a stage in their development that makes them accessible to the target market and in the locations where the design will be produced and used. In practice this can be difficult to determine but the notion of Technology Readiness Level (often referred to as "TRL") can be a useful tool for assessing the maturity of a given technology (Wikipedia, 2020a). While widely used, there are limitations to the use of TRLs that are highlighted by Olechowski et al. (2020) who reviewed the experiences of practitioners and identify improvement opportunities.

1.2.2 Design ethnography

Designer-driven design allows broader insights by building on theoretical frameworks from the social sciences, specifically anthropology which studies human cultures and the roles of artefacts in people's lives. Design ethnography is a social science research method that is applied in design to build insights in difficult to access or future design challenges. In an engineering design context, Wood and Mattson (2019) provide a brief history of design ethnography and its application by designers designing for developing communities of which they are not a part. There are also numerous examples in the literature where design ethnography has been used to inform design requirements. For example, Hamzah et al. (2018) report an ethnographic study of paediatric oncology patients that was used to inform the requirements for computer games, and Larsen (2017) reports an ethnographic study of bicycle parking that highlights requirements for cities' cycling and wider mobility infrastructures. In engineering design, a number of authors anticipate the emergence of a new range of tools for use in design ethnography. Dixon et al. (2016) provide a review of the state of the art in computer-aided design ethnography that exploits a range of emerging computational approaches and example applications are emerging in the literature. For example, Favero and Theunissen (2018) introduce *EthnoAlly*, a data collection tool that includes a smartphone app and associated archiving and analysis platform.

1.2.3 Vision in Product Design

Hekkert and van Dijk (2016) propose Vision In Product Design (VIP) where designers envision new future scenarios for which they then design and innovate. Their approach encourages analysis of the designs of existing products from three perspectives: the product as a stand-alone artefact, ways in which users and the product interact with each other, and the context within which the product is used. These analyses identify design goals that form the basis of subsequent design processes where the focus lies in designing for future contexts. A series of product design case studies are provided in (Hekkert and van Dijk, 2016). McKay et al. (2008) outline a similar, context-driven, approach that encouraged students to design products for more sustainable futures that they envisioned using research in product-related problem areas for sustainable development such as plastic carrier bags, toys and mobile phones. A key point for designer-driven approaches to the identification of design goals lies in the designer envisioning future situations and scenarios. Hughes et al.'s systems scenarios tool (2017) is a tool that can be used to articulate such futures through the description of user scenarios.

1.3 Systems approaches

Current practice in understanding stakeholder needs and so design goals in large complex, engineered systems tend to combine user- and designer-driven approaches to design specific system components, with systems-based methods to provide insights into wider, system-level, needs and so goals. For example, results of participatory design processes are often documented in the form of completed game boards, storyboards depicting future scenarios (which consider the design in the system that will form its context of use) and flowcharts defining new processes within these scenarios. If you have used these methods to describe problems you are tackling or potential solutions then you will probably have noticed that much of the richness you found was not captured. This is because storyboards capture snapshots of a story or experience, and flowcharts really only capture process steps and flows between them. They are fine if this is what you want, but when you are designing solutions that are to form parts of wider systems you often need more than what you can capture in a flowchart or storyboard.

A system is a collection of interconnected parts that serve some purpose. What this purpose is usually varies depending on the perspective you take. For instance, the purpose of an oilrig from the perspective of its owner may be extract oil, whereas for a consumer of oil-based products it may be to provide fuel. Both, and numerous others, are valid perspectives that cover the needs of multiple stakeholders. Systems thinking is a useful way to consider stakeholder needs, and so design goals, because it provides insights into structures and relationships between elements of the system being designed, wider systems of which it is a part and other systems to which it is connected. For example, systems thinking can allow you to improve understanding of the organisational structures that influence how people behave, appreciate wider implications of proposed changes, and see bigger pictures that may impact the success of the design.

In this section we introduce three systems-based approaches to understanding stakeholder needs and so design goals. Each provides a different kind of view on the system under consideration. In systems engineering (sometimes referred to as "hard systems") approaches (Section 1.3.1), where the focus lies on physical engineering system interventions, needs and goals are derived from a Concept of Operations (ConOps) (Fairley & Thayer, 1997, (Wikipedia, 2020b)) and articulated through a target capability statement and design requirements. However, systems engineering approaches provide limited insights to the social dimensions, people and organisations, of the system. Soft systems thinking (Section 1.3.2) was established to enable debate, and so development of insights into social aspects. Finally, we introduce principles and tools for socio-technical systems design (in Section 1.3.3) which provides methods for considering both social and technical aspects of a given system.

1.3.1 [Hard] systems engineering

Systems engineering approaches, used in the development of technical components of socio-technical engineering systems, emphasise so-called "hard systems" perspectives in the context of wider user and stakeholder needs. Hard systems perspectives focus on the technical artifacts that are integrated to form larger complex products and socio-technical systems. Blanchard and Fabrycky (2011) is the definitive systems engineering textbook. As such it includes a systems design process, applications of systems modelling, and analysis methods to support the verification and validation of design concepts from both functional and operational perspectives. Blanchard and Fabrycky's systems engineering vee model is widely used in industry and numerous versions of the model have evolved since it was originally proposed. The UK's Royal Academy of Engineering provides six principles of systems engineering which include using the systems engineering vee model. The RAEng version of the vee model (Elliot and Deasley, 2007) is provided in Figure 2. Key features of all vee models are: the flow of design requirements down the left-hand side of the vee; the flow of realised solutions up the right-hand side of the vee; and the zigzagging between the two sides of the vee where parts of systems, components and sub-systems, are tested against requirements at each level of decomposition of the system. McKay et al. (2020) provide a version of the vee model that allows its application to the design of systems without the need for a system realisation process. In this model, which is an elaboration of the left-hand side of the traditional vee model, design requirements flow down the left-hand side of the vee, design solutions flow up the right-hand side and the zigzagging process evaluates proposed designs against design requirements. However, when using these vee models, there is an assumption that the initial design goal, the capability statement in the RAEng model, is an accurate reflection of the stakeholders' needs.

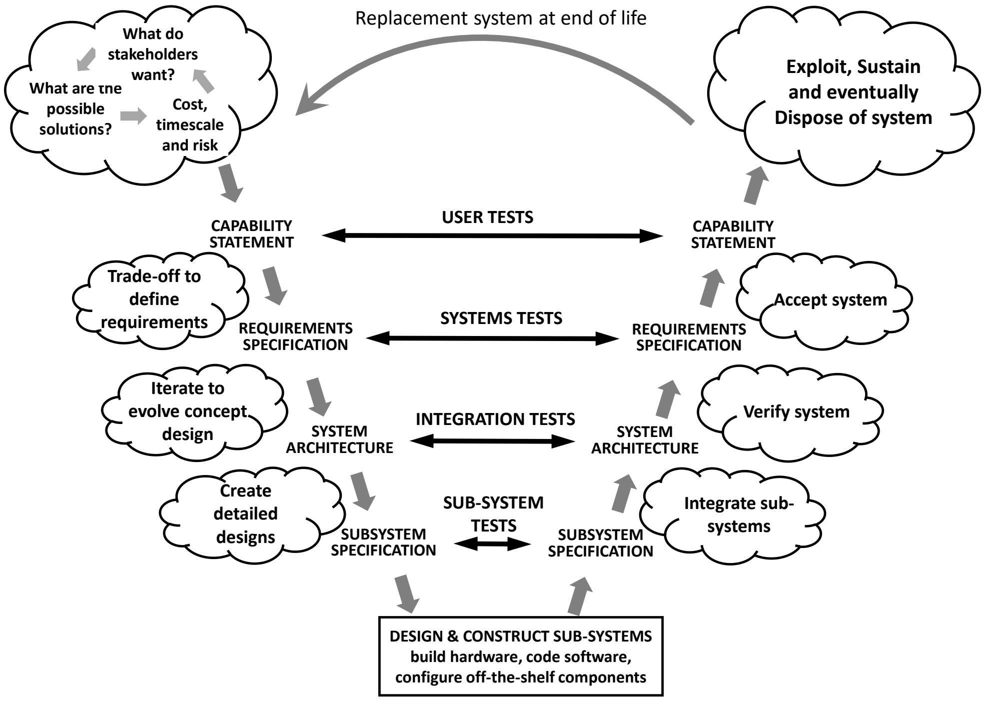

Figure 2: The RAEng systems engineering vee model (adapted from (Elliot and Deasley, 2007))

Stakeholders' needs are touched upon in the top, left-hand corner in Figure 2 with the questions: *What do stakeholders want? What are possible solutions?* and [What is acceptable in terms of] *cost, timescale and risk?* However, answering these questions is not straightforward. The discipline of requirements engineering emerged in the 1990s as an important part of systems engineering. Hull et al. (2011) provide a process for requirements engineering that is applied at all levels of the systems engineering vee: in both problem and solution domains, i.e., at the top and lower levels of the vee respectively. The focus of this chapter lies in requirements engineering in the problem domain where the requirements engineering process itself includes four key steps:

(1) the elicitation of requirements from within the problem domain;
(2) analysis and, where necessary, negotiation of requirements with stakeholders;
(3) documentation and specification of requirements; and
(4) validation of requirements to produce an agreed set of system requirements.

A key aspect of systems engineering is the traceability that supports the effective management of change (Hull et al., 2011). Hull et al. (2011) show how traceability and change can be managed within a collection of system requirements and Agouridas et al. (2008, 2006b) provide a mechanism for relating system requirements to stakeholder needs. In this way, if stakeholder needs change, implications for system requirements can be derived and the use of a systematic process for deriving stakeholder requirements can help identify previously unseen needs (Agouridas et al., 2006a).

1.3.2 Soft systems approaches

While [hard] systems engineering includes methods for considering the wider contexts within which an engineered or technical system will be operated and supported through life, the focus of these methods is on the engineered system rather than the wider system of use and its goals. As requirements engineering processes delve deeper into the needs of stakeholders, the importance of understanding wider, often social and organisational, factors and contexts that influence how they use, work with, and benefit from engineered systems grows. In contrast to hard systems approaches, soft systems methods (Checkland, 2000) consider social systems that include multiple people, often belonging to multiple organisations and where both the people involved and their organisations have different, possibly conflicting, goals and values. This focus on wider, social, perspectives makes soft systems methods well suited to resolving real-world problems where the development of workable solutions requires debate and different parties gaining insights into others' goals and needs.

Checkland and Scholes (2000) provide a cyclic four stage model for learning from the application of soft systems thinking (see Figure 3). The process focusses on a real-world problem situation, which, in a systems design project, could be captured in a problem statement or project brief. Based on this, multiple 'Relevant' Models, in the form of rich pictures and conceptual models, are defined and used, in conjunction with wider knowledge of the problem situation, as the basis of a structured debate. Outcomes from this debate are used to identify improvement opportunities (which could be requirements for new engineered systems) and so improve understanding of the real-world problem and so the models and subsequent debates.

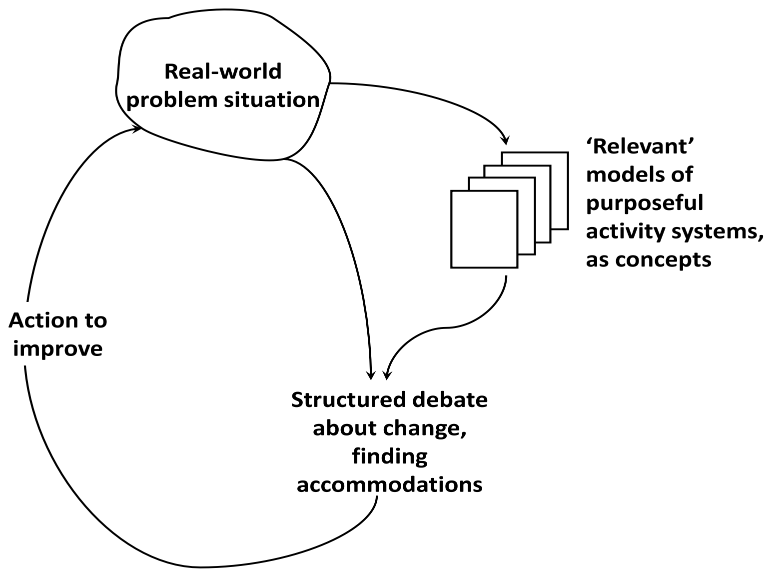

Figure 3: Checkland and Scholes' four stage learning cycle model (Adapted from Checkland & Scholes, 1999)

As shown in Figure 3, the soft systems approach begins with the development of one or more rich pictures which are drawings and diagrams that depict the real-world problem situation and the stakeholders associated with it. These inform the development of conceptual models, each of which is a relevant model in Figure 3. Unlike rich pictures, each conceptual model has a specific structure that includes a root definition and a CATWOE analysis. The root definition defines the purpose of the system in terms of a transformation from the viewpoint of a given stakeholder, and is used to inform a CATWOE analysis which identifies the **C**ustomer, **A**ctors, **T**ransformation, **W**eltanschauuung (World view), **O**wnership, and **E**nvironment.

Soft systems approaches are widely used for gaining insights into the operations of human activity systems and in the design and development of IT systems for such contexts (Checkland and Holwell, 1997). However, the focus lies on the human activities that drive the system and the delivery of its goals rather than the design of technical aspects of the system itself. In this way, the soft systems approach encourages discussion and provides opportunities for deep exploration of a problem area.

1.3.3 Socio-technical systems thinking

Soft systems approaches are useful in planning and implementing change, and for engaging stakeholders in such processes. However, when engineered products and systems are to be parts of solutions, there is a need for more structured approaches. Such approaches need to consider factors that are important to the successful deployment of technological solutions, such as available infrastructures and the capabilities of people who will be interacting with the system. Socio-technical systems design enables this by providing methods to consider systems that include both social and technical components (Clegg, 2000; Clegg et al., 2017), and so enables the integration of the hard and soft systems discussed above.

Socio-technical systems approaches emerged from the academic disciplines of organisational and work psychology. The rationale for applying these approaches to systems design is that failure to do so can increase the risk that designed systems will not make their expected contribution to the goals of the organisation in which it will be implemented (Baxter & Sommerville 2011). Socio-technical systems approaches combine two types of system perspective (McKay et al., 2020):

(1) *Technical systems* that are produced and continuously adapted to provide a reliable and predictable relationship between user input and the system's output; and
(2) *Social systems* that are the result of continuous evolution including emergent changes and behaviours.

As a result, applying the socio-technical systems approaches can result in conflicting value systems. The first set of values is a fundamental commitment to humanistic principles, where the designer is aiming to improve the quality of working life and wellbeing of employees. The second set is of managerial values, focused on using socio-technical systems approaches to help achieve an organisation's objectives. Problems may arise when these different sets of values come into conflict (Baxter & Sommerville 2011).

Socio-technical systems approaches provide ways of designing systems that include human and organisational behaviours and technology. In this way, they enable the often overlooked but critical social elements of engineering systems to be considered (Robinson & Drury, 2020). Some of socio-technical theory draws on the academic discipline of organisational psychology, which considers human behaviour and cognition in work contexts, including organisational processes, culture, and technology (Crowder et al., 2012). More background on the genesis of socio-technical systems approaches and their potential role in design is provided in Clegg et al. (2017). Baxter and Sommerville (2011) also provide a review of socio-technical systems approaches with a focus on the design of computer systems. Socio-technical systems approaches provide insights on how interactions between human and organisational behaviours and technical solutions influence overall system behaviours (Challenger et al., 2010). Clegg et al. (2017) provide a hexagonal framework, shown in Figure 4 and adapted from earlier work by Clegg (1979), that can be used to represent a given socio-technical system at levels of detail ranging from individual people through to teams and organisations.

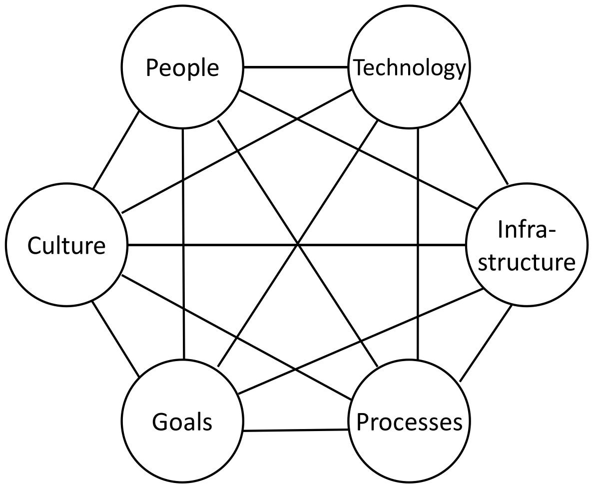

Figure 4: Socio-technical systems hexagon. Reproduced from Clegg et al. (2017).

Analyses of systems using the hexagon focus on six aspects of socio-technical systems thinking. People, culture, and goals focus on social systems aspects, such as organisational culture, social networks and leadership, and, in this context, individual and group behaviour and cognition. This includes, for groups, team working, leadership, and communication (Crowder et al., 2012), and, for individuals, competencies, training, and wellbeing (Robinson et al., 2005). The other three aspects focus on the development and use of technology in social systems, including ways in which technology is integrated with people's work, how this and the design of workplaces and other infrastructures impact performance, and the processes that integrate these. Davis et al. (2014) provide a ten-step description of how to analyse and understand existing socio-technical systems. The range of diverse application areas is illustrated by applications of the approach to case studies. For example, analysing the 1989 Hillsborough football stadium disaster in the UK, implementing environmental sustainability in manufacturing, and preparing for and managing major events, such as the London 2012 Olympics, where a hexagon analysis identified the potential risk factors within the large-scale system that could impact on crowd management and safety.

A key aspect of all forms of systems thinking is the importance of taking a holistic view. For example, in socio-technical systems, there are numerous reports of system failures that can be attributed to a failure to consider social aspects of technological changes and to focus on the development of technology without consideration of wider factors (Clegg & Shepherd, 2007). There are several socio-technical methodological approaches that have been developed to elicit information from stakeholders and experts about systemic problems, to identify and mitigate potential systemic failures, and to identify effective systemic processes. We outline two such examples here.

First, Hughes et al. (2017) introduced a Systems Scenario Toolkit to help design or redesign work systems. The toolkit helps explicate the choices made consciously or unconsciously during the design of a work system through consideration of different representative scenarios. The toolkit is a series of workshops and includes six broad stages from involving stakeholders to making choices and agreeing on an action plan to transition from the less effective 'as-is' to the more effective 'to-be' system. The specific goal of redesigning a work system is therefore realised through the interaction of stakeholders in a workshop. Second, Read et al. (2018) developed a toolkit for information and guidance on analysing complex socio-technical systems, including a requirements identification template. The requirements may assist in planning the system design process, which also includes establishing a design brief and design criteria to help develop a shared understanding of the design goals, both within a project team and between the project team and users and stakeholder representatives.

Overall, thinking about the lifecycle (including use) network of an engineering system is a useful way to identify the stakeholders whose needs it is important to consider. Stakeholder analysis is a tool for understanding the needs of people with an interest in a project (McDonald, 2015). Much of the guidance on stakeholder analysis tends to focus on the needs of individual people or groups of people, as opposed to people in organisations whom we also consider here. Once they have been identified, there is a wide range of methods and tools for understanding stakeholder needs, values and, goals.

1.4 How to apply the state of the art

Thus far, we have introduced a range of methods and approaches that can be used to build an appreciation of stakeholder needs and design goals. While they provide numerous opportunities to gain insights, they also create a problem in that practitioners need to decide which approaches are best suited to the design challenge they are tackling. Accordingly, we provide two categorisations of the approaches that have been introduced. The first, in Table 1, groups the approaches based on the extent to which the design goals are quantified and how structured the approach is. If these approaches are regarded as tools then, like any collection of tools, some are more suitable for different tasks or different stages in a given task than others. For example, design thinking processes and tools are well suited to design processes when empathising with target users, finding out who they are, and understanding their needs is necessary. On the other hand, if the target users are organisations and people in organisational contexts then more formal requirement management processes from systems engineering are likely to be more suitable. Furthermore, later in the process, when a broad understanding of needs has been achieved and design goals are fixed, approaches that involve more quantification of design goals are likely to be more appropriate. For example, the early stages of engineering design processes (Pahl et al., 2006; Pugh, 1990; Ulrich & Eppinger, 2004) or methods from the disciplines of ergonomics and human factors (Hughes et al., 2017; Read et al., 2018).

Table 1: Approaches for the development of stakeholder needs and design goals

		Quantification of needs & goals	
		Low	**High**
Structure in the approach	**Low**	Participatory design (1.1.2) Design thinking (1.2.1) Design ethnography (1.2.2) Vision in Product Design (1.2.3) Soft systems approaches (1.3.2) Socio-technical systems thinking (1.3.3)	Although out of scope for this chapter, once design goals and stakeholder needs have been established, early stages of any subsequent engineering design process will include the quantification of needs and goals as part of its requirements definition processes.
Structure in the approach	**High**	[Hard] systems engineering (1.3.1)	User-centred design (1.1.1)

A second categorisation scheme is provided by Karsh et al. (2014) who introduce a framework that includes three levels of system decomposition:

(1) macro (relating to industries, nations, and global issues such as the planet and societies);

(2) meso (covering organisations, departments, groups, and teams within an organisation); and

(3) micro (including individual people and their immediate work environment).

What constitutes macro, meso, or micro depends on the level of socio-technical system decomposition at which you are working. For example, if you are focussed on individual users then teams may be regarded as meso whereas if the focus of a design effort is directed towards teams then the team may be regarded as the micro level. Referring back to Figure 1, this can be seen as a meso level decomposition of the lifecycle system for an engineered product because the elements are organisations within this network. However, this network could also be modelled as a part of a wider, industrial (macro) system and each part of Figure 1 could be modelled in more detail as a micro level system, for example, by detailing the way in which the input to a given organisation is transformed by individual people and teams into its output.

Given the range of methods introduced in this chapter, readers may have the impression that identifying and capturing stakeholder needs, and translating them into design goals, is a straightforward one-off process that sets the stage for a design activity. The reality is somewhat more complex, however, so we conclude this section with two caveats.

1) In practice, design (including understanding stakeholder needs and design goals), is an iterative process where understanding gained later in the process creates a need to revisit earlier stages of the process. For this reason, considering stakeholder needs is an essential theme throughout entire design processes rather than a one-off task.
2) Developing design goals can create ambiguities surrounding what the object of a given design activity is. For example, we are writing this chapter at a time when the need to

address climate change is high on many people's agendas. In this situation, the planet may be regarded as a macro-level system in Karsh et al.'s (2014) framework. Although designers can create so-called "green" products and people might use them in large numbers, these actions alone are unlikely to solve the global problem of climate change and often solutions have unintended consequences. For example, the move to bio-fuels can take land from food production. Individual designers are unlikely to be able to solve such global issues due to the wicked nature of such problems single-handedly, and the best they are able to do may be to design in the context of wider organisational and societal goals. For this reason, some of the needs and goals uncovered may not become direct design goals; rather, they form contexts within which system design activities are conducted.

2 Case studies

We conclude this chapter with three case studies. Two illustrate applications of the methods introduced in Section 2: the first relating to the design of a product for use in a healthcare system, and the second to the design of a knowledge management system to connect the design and operations of an oilrig. Both of these case studies build on our experiences from projects where the need to understand design goals and stakeholder needs was critical. With respect to Karsh et al., the first relates to the design of a micro-level engineering system, the design of a medical device for a neurosurgical application. In this example, recognition of individual stakeholders' needs, and the resources available to them from the wider system within which the product was to be used, were critical factors in the success of the overall design. In particular, there was a need to trade-off accuracy (sub-cm was required as opposed to sub-mm in current solutions) against set-up time (10 minutes was required as opposed to hours or days in current solutions). Secondly, we complement this example with a meso-level example, based on the development of a knowledge management system to support the design and operation of an oilrig that provides insights into stakeholder needs arising from the lifecycle support for a large, complex product. At this level in the wider system, knowledge management and sharing are important factors in the successful operation of the oilrig and the oilfield of which it is a part (Grant, 2013). We finish with a third case study, a macro-level system in Karsh et al.'s framework, that explores the potential applicability of the approaches introduced in this chapter to a current societal challenge, namely sustainable development. Together, these case studies typify the many sources of design goals that need to be appreciated in the design of complex, socio-technical engineering systems.

2.1 Stakeholder needs in a medical device design project

Our first case study focusses on understanding stakeholder needs for the design of a medical device for use in neurosurgery based on a user-centred approach delivered through a multi-disciplinary student team project involving two product design students, two mechanical engineering students and a neurosurgeon. The design brief, set by the neurosurgeon, was to design a localization system for emergency neurosurgery. In such situations, neuro-surgeons used localization technologies to select an entry point when planning surgical procedures. For procedures such as the insertion of ventricular shunts and drainage of blood clots, abscesses, cysts, and tumours, neurosurgeons must operate on the specific regions within the brain that are affected, with an accuracy of less than 1cm.

Two common localization technologies used at the time of the project to achieve this degree of accuracy were stereotactic frames and image guidance systems. The use of both technologies required the availability of sophisticated equipment (and highly trained staff to operate it) and took a significant amount of resource and time. These constraints made the technologies unsuitable for use in emergency situations where the ability to treat patients quickly is a high priority. In such situations, neurosurgeons typically operated "blind", using their knowledge of the anatomy of the skull and brain to localize the treatment. The goal of this project was to find a more efficient and effective way of localizing points in the brain to sub cm accuracy. Efficiency, in this context, was measured in terms of cost, time, and resource utilisation, while effectiveness was measured in terms of responsiveness to clinical needs, and reduction of radiation dosage for patients. It was anticipated that this would improve the efficacy and effectiveness of treatments for patients primarily in emergency situations but also with the ability to aid elective procedures. The project resulted in the physical prototype and associated software shown in Figure 5. These were derived from and evaluated against design requirements, in the form of the demands and wishes (Pahl et al., 2006) shown in Table 2. The prototypes and candidate designs were evaluated against these requirements through analysis, simulation, and user and product testing. The final design, including both physical and software components, was accepted by stakeholders but a subsequent patent search concluded that the design team did not have the necessary freedom to operate and so the project can be openly discussed.

Figure 5: Illustrations of design outcomes

Table 2: Neuroframe design requirements

Demands	**Wishes**
The design must:	The design should:
(1) point to a location with an accuracy of 1 square cm	(1) be as simple as possible to use (no highly specialised staff required)
(2) have a setup time not exceeding 10 minutes	(2) be simple to assemble/disassemble
(3) be inexpensive and intuitive to operate (relative to current methods, i.e. stereotactic)	(3) allow the surgeon the required freedom of movement to perform necessary tasks efficiently
(4) convert output data from an original CT scan based software into a physical localization	(4) be accompanied by a checking rig to allow accuracy confirmation and error checking in use
(5) be used in conjunction with the Mayfield clamp	(5) be applicable to a wide range of emergency situations

(6) be suitable for pre-operative use in a marking out/visualisation aid role for making initial marks on the patient's skin	

The design process focussed on a real-world problem situation which, in a systems design project, could be captured in a problem statement or project brief, such as the initial design brief in the neurosurgical case. For example, the design team developed soft systems rich pictures and conceptual models that they used to inform discussions with the neurosurgeon who brought wider knowledge that may not have been captured in the models. These models were informed by information gathered from a visit to the neurosurgical unit and discussions with members of the wider team including other doctors and nurses.

The neurosurgical device included wider, system level, needs in its design requirements. For example, in its operation-related requirements, hard systems perspectives identified a need to interface with technical systems within the hospital, such as a Mayfield clamp, a standard piece of equipment in the neurosurgical unit, which led to an operational requirement for the solution to be simple to assemble and integrate with the Mayfield clamp. However, the majority of the design requirements were related to medical priorities (e.g., setup time, use of available data (the CT scan)). The demand for an accuracy of 1 square cm was agreed with stakeholders as a valid interpretation of "sub cm accuracy" and the demand to integrate with a Mayfield clamp was uncovered from discussions with stakeholders and essential because it is a standard piece of neurosurgical equipment in the majority of neurosurgical facilities. The requirement to be intuitive to use relates to users' previous experiences and expertise, and being suitable for pre-operative use was identified as a requirement during user testing when this emerged as an opportunity. From this example, we can see a number of factors that influence relationships between design goals and stakeholder needs and so need to be taken into account in the design of engineering systems. These include the need to iterate design goals through the design process; the importance of engaging with users and other stakeholders, both when defining initial design goals and through the design process; and the importance of building understanding of social and technical aspects of the systems within which a product will be used. All of which are aspects of the design thinking process (Lewrick et al., 2018, Mabogunje et al., 2016).

2.2 Lifecycle and organisational perspectives from an oilrig design project

Our second case study focusses on the design of a knowledge management system. When complex socio-technical systems are regularly renewed, there is a need for feedback from the operations life-cycle phase into the development and design phase. In this section, we introduce a case from the offshore oil industry (Conceicao et al., 2019). The company operates a number of offshore drilling rigs, and, at the same time, develops and designs new rigs for future operations. For this reason, an oilrig that is functionally excellent on delivery but difficult and costly to maintain and operate is unlikely to be an acceptable solution. Hence, in order to optimise the designs of new rigs, the company wanted to improve the transfer of knowledge and experiences from the operation of rigs into the design processes of new rigs. A group of researchers were invited to improve this knowledge transfer process. Their intervention, using a participatory design approach, was based on involving relevant stakeholders in two workshops with the aim of creating conceptual designs for a new knowledge transfer system.

The case company was organised into two main divisions: operations and engineering design. Thus, the overall socio-technical system included both offshore drilling rig operations and onshore engineering design subsystems. The company had different systems in place for transferring operational information, such as reporting of safety incidents and equipment breakdowns, from the rigs to the onshore headquarters. However there was no dedicated system to capture operational experiences that were important to the design of a new rig.

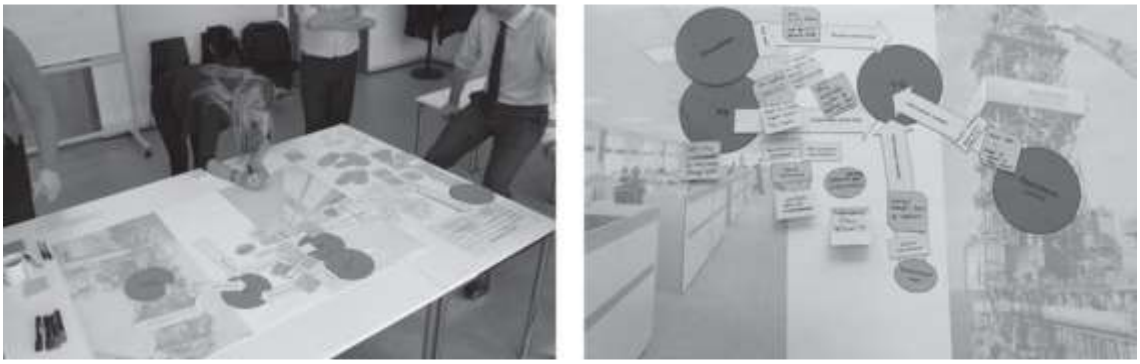

Figure 5: Workshop with stakeholders working with design games. From (Conceicao et al. 2019)

The workshops were organised by the researchers, each two hours in length. The first workshop identified design goals and stakeholder needs, explored the existing knowledge transfer system to understand the current practices, and set systems design requirements. The second workshop developed ideas for design of the knowledge transfer system and setting up systems requirements. The first workshop had five participants from the engineering design division, and the second had eight participants from both offshore rig operations and onshore engineering design. The format of the workshops was based on principles from participatory design and included design games, visualization techniques and tangible materials such as game boards and game pieces, as shown in Figure 5. The researchers, who had agreed workshop goals and rules for 'playing' the design games, facilitated the workshops. The participants stood around a table with the game board and game pieces.

The first workshop included two design games aimed at elucidating the current flow of knowledge between the offshore rigs and the engineering design department. Shortcomings and areas that needed improvement were identified. In the second workshop, the main activity was a design game in which the participants simulated a possible new system for knowledge transfer. Based on scenarios, the participants systematically explored how knowledge was captured in the rigs, and then transformed, transferred, and applied in the engineering design department. The outcome of the two workshops was a system requirement list for each of the four steps in the knowledge transfer process (Figure 6): capturing, transforming, transferring, and applying.

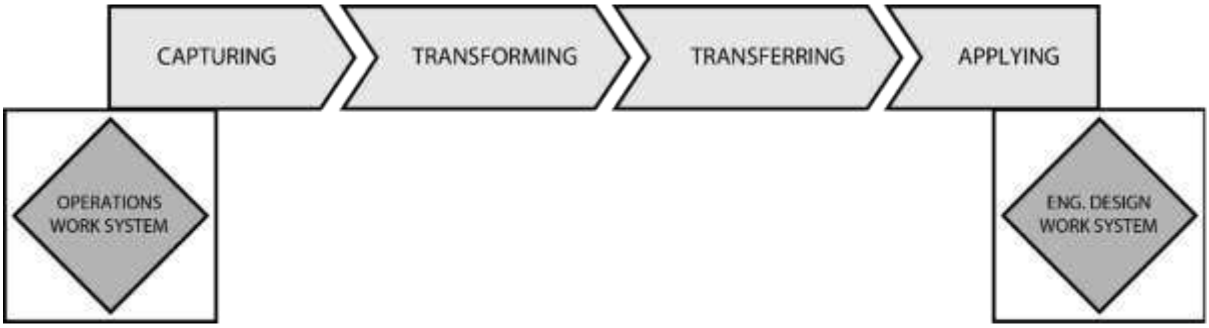

Figure 6: Four-step model of knowledge transfer from rig operations to engineering design of a new rig. (Conceicao et al. 2019)

This case illustrates how workshops based on design games can facilitate stakeholder participation in identifying stakeholder needs and setting design goals for the design or redesign of complex socio-technical systems. The case especially highlighted two benefits. Firstly, representing the socio-technical system from a bird's-eye view in a game board gave all participants an overview of all processes and structures, even if, in their daily work, they were embedded in a different part of the wider system, thereby building shared team mental models (DeChurch & Mesmer-Magnus, 2010). Because of stakeholder representation from all parts of the system, it was possible for workshop participants to zoom in and out on specific parts of the system to clarify current practices or explore new ways of working. Secondly, the combination of setting goals and rules for the workshops, having a facilitator who can trigger action, and using open objects as game materials enabled the participants to take a design-oriented approach. They focussed on switching between collaboratively exploring current practices and redesigning these practices to improve the overall knowledge transfer system.

The case also illustrates that often it is not possible to identify a single designer or group of designers who are in charge of designing a new system. Rather, there are many potential designers across organisational boundaries and there are many user groups. Socio-technical systems design is a multi-stakeholder design approach. In this case, the researchers adopted temporary roles as designers to set up a participatory design process and, through the process, the participants learned about each other's work practices and mind-sets. The simulation activities enabled participants to try out organisational changes, including structure, processes, and tools. Simulating the future knowledge transfer system allowed the stakeholders to learn from practice without incurring real-world risk. Finally, the case indicates that setting design goals is not a one-off occurrence in systems design. During both workshops, both what improving the knowledge transfer system meant and what the design goals should be were discussed continuously. The goals developed and became more specific along the process in the interaction between the stakeholders.

2.3 Designing for sustainable development

The United Nations (UN) provides 17 goals for sustainable development (2020). Although engineering systems are likely to have a role to play in the achievement of each of these goals, three are particularly pertinent to the development, lifecycle support and disposal of all engineering systems: promoting sustainable economic growth, ensuring sustainable patterns of consumption and production, and combatting climate change. A real challenge, however, lies in balancing these three goals and the contradictions that they create. For example, manufacturing industries make a significant contribution to the achievement of economic growth but also contribute to climate change and may drive unsustainable patterns of consumption and production. Further, the roots of many of the solutions to issues highlighted through the UN goals are likely to sit in the hands of policy makers and citizens rather than engineers and the systems we produce. Being wicked problems, it is not possible to create single solutions that address all 17 goals. As a result, like today's engineering systems, future engineering systems are unlikely to provide complete solutions. Instead, engineering systems will provide interventions that, in the context of policies and changes in citizens' behaviours, will improve situations and so move us towards achieving the UN goals.

In a recent keynote presentation, Maier and Eppinger (2019) characterised the challenge of designing for sustainable development as a journey. Current approaches such as eco-design and work towards achieving circular economies are early steps in this journey but there are many challenges to overcome. One of these challenges lies in finding ways to formulate design requirements against which the whole life sustainability of design options can be evaluated as a part of the design process. This, in turn, leads to another challenge in that today's design evaluation tools for large, complex engineered systems apply the laws of physics that govern the behaviour of systems but not how users and other stakeholders use and operate such systems. A prerequisite for improving design evaluation tools in this way lies in gaining deeper insights to stakeholder needs and design goals. In the remainder of this case study we highlight opportunities for ways in which the approaches introduced in this chapter could contribute.

Systems-based approaches were introduced in Section 1.3. Socio-technical systems thinking encourages the consideration of both technical and social dimensions of a problem as an integrated whole. However, designing large-scale socio technical systems usually involves the design and deployment of interventions that steer or nudge (Thaler and Sunstein, 2009) the system in a more desirable direction rather than creating a radically new system from scratch. This is because there are usually legacy effects, in terms of both social and technological aspects, meaning that we are designing for so-called "brown-field" sites. As such, designers design interventions to existing socio-technical systems rather than design from a blank sheet. Given a design challenge, soft systems approaches can add value by providing opportunities to include a wide range of stakeholders in constructive debate. This allows designers to gain more nuanced appreciations of the people they are designing for and the practicalities of the lives they lead which, in turn, have a significant impact on the viability of proposed solutions.

An important consideration in the use of systems approaches lies in where to draw the boundary of the system under consideration. Draw it too wide and you'll have an intractable problem, draw it too narrow and the system level concerns to be addressed risk being out of scope. Dorst (2015a) proposes frame innovation that can be used as a means of drawing alternative system boundaries. Frame creation is well suited for solving large-scale open, complex, dynamic and networked problems. A main step in the framework is to reformulate, or reframe, the problem at hand. Creating a frame means developing a novel standpoint from which a problem can be solved. In doing this the system’s borders are broadened, and new stakeholders are included. Understanding the goals and needs of the stakeholders in this broader system is a way to open up new solution spaces. Dorst (2015b) provides an example application of frame creation to address a large-scale, complex problem that impacts sustainable development goals. The case involved the construction of a tunnel for the A9 highway around Amsterdam. The tunnel was aimed at improving air quality and reducing sound levels around one of the road’s bottlenecks. However, the construction would take about five years and the work would have an environmental impact, including on residential neighbourhoods and office buildings. The design project was characterised by conventional planning and control policies, complex processes and a tight budget. In a situation with complaints and discontent from affected stakeholders in the area, a suggestion was made to investigate the relationship between the construction works and the surrounding areas by creating a frame. The following frame was identified: *“What if you could see the building of the tunnel as a new ‘temporary economy’? What new connections could we make then?”* (Dorst 2015b, p. 29) In this way stakeholders, including residents, office workers and commuters were included in the system design process. By studying the lives and minds of this wider group of stakeholders, new frames emerged for the construction project. The construction project was now seen as a ‘temporary economy’ in which the construction workers were seen as temporary inhabitants who needed to be supported by local services that later on could become permanent. This opened up opportunities for the creation of new initiatives including bespoke food stalls, childcare services, new courses at the local vocational training centre, and establishing new local firms to deal with the waste materials from the building works. This case illustrates the value of spending resources on problem framing in the design of large-scale, complex systems. The conventional planning and control approach was complemented by the new frame which regarded the local community as a source of innovation who contributed to a deeper understanding of stakeholders needs and design goals which, in turn, opened opportunities for new design solutions.

With an appropriate capability statement that reflects relevant stakeholder needs and design goals, hard systems approaches can be used to design and develop new improved solutions. However, to include human aspects, designer-driven approaches can be used to complement hard systems approaches. Design thinking processes can facilitate this through their focus on the desirability, viability and feasibility of proposed solutions. In the context of processes such as design thinking, design ethnography can be used to uncover insights into the needs and wants of hard-to-reach communities and users. It is important to remember that many of the factors that affect the sustainability of design solutions are related to how products are used (and so human and organisational behaviours) and available infrastructures (e.g., to maintain and repair products, and to process them at end of life) which affect the feasibility and viability of proposed solutions. Given insights from such processes, however, participatory design and user-centred design can be used to inform the parts of systems with which people (be they users or other stakeholders who support the product through its life) interact.

F. CONCLUSION

3 Conclusion

In this chapter, we have introduced a range of methods used to understand stakeholder needs, and so design goals, in the design of complex engineered products and the socio-technical systems in which they are developed and used. Three case studies were used to illustrate the applicability of these methods to the design of a surgical device, the design of a knowledge management system and the design of solutions that respond to sustainable development goals. A key aspect of all approaches and the three case studies is the consideration of the wider, socio-technical contexts within which target users and others who have a stake in the product through its life will interact with the product and its effects. Traditionally, the kinds of systems approaches introduced in this chapter have been used largely in the design of high value, complex, long-lived products such as aeroplanes and ships, where operational costs typically exceed (often by an order of magnitude) the costs of developing such products, especially when products or the infrastructures within which they live fail. Increasingly, though, especially given increasing awareness of climate change and societal demands for action, engineering design teams will also need to adopt these approaches for lower value products where stakeholders will include the planet and products will be designed, used, and discarded in the context of closed lifecycle systems such as those promoted by protagonists of circular economies.

This chapter covers methods for eliciting user and stakeholder needs, and so design goals, but systematic processes for using such approaches or translating their results into design requirements remain to be found or defined. What we do know is that the process of developing stakeholder needs and design goals is iterative and continues through the design process as learning about the problem being addressed grows and the product's context of operation evolves. For example, the development cycle for a complex, engineered product can be several years long, in which time information technology advances can have a significant impact on how a product will be used and the technologies that will be embedded within it. A widely used approach for articulating design requirements in the systems engineering community is Concept of Operations (ConOps) which provides, in the language of users, a description of how the product is intended to be operated. While this is useful, a key challenge lies in how design goals and high level design requirements such as ConOps are broken down into requirements for sub-systems. This also affects the translation of socio-technical system level requirements into product requirements.

In future design practice, we anticipate that designers will increasingly design products in the contexts of wider systems, where they will need to work with less deterministic, more stochastic information such as that related to climate systems and associated with human behaviours. This is likely to become increasingly important in the development of design requirements. As can be seen from the systems engineering vee (Figure 2), high-level design requirements are not simply decomposed into more detailed requirements; instead, there is a zig-zagging process where solution principles are fixed. Solution principles, in turn, inform both the overall architecture of the product and how requirements are allocated to different aspects. For engineered products that are parts of socio-technical systems, these early, system-level, decisions involve the allocation of functions to social and technical aspects of the system (Challenger et al., 2013).

In future research, we see a need for further work on systems design, addressing what can or cannot be designed, what should be left to emerge, and the impacts of local, regional, national and international policies. There are also emerging opportunities for new methods and interventions through the lives of products and design practice will need to adjust to this. Technological advances will undoubtedly transform this landscape too, enabling design and other processes such as manufacturing to be more closely integrated through, for example, the increasing use of big data and artificial intelligence in engineering (Tao et al., 2018) and the use of digital twins for simulation (Cai et al., 2017).

4 Acknowledgements

The oilrig design project was carried out in collaboration with Dr. Carolina Conceicao, DTU-Technical University of Denmark, Engineering Systems Design Section at the Department of Technology, Management and Economics and was co-funded by the Danish Maritime Fund. The neurosurgery case study was carried out by four students (James Hyson, David Lewis, Stephanie Prince and Emma Routledge) in response to a brief set by Mr Nick de Pennington who, at the time, was a neurosurgeon at the Radcliffe Infirmary in Oxford.

G. REFERENCES

Agouridas V, Marshall A, McKay A, De Pennington A (2006) Establishing stakeholder needs for medical devices. Proceedings of the ASME Design Engineering Technical Conference, September 10–13, Philadelphia, Pennsylvania, USA

Agouridas V, McKay A, Winand H, De Pennington A (2008) Advanced product planning: A comprehensive process for systemic definition of new product requirements. Requirements Engineering 13**:** 19–48

Agouridas V, Winand H, McKay A, De Pennington (2006b) Early alignment of design requirements with stakeholder needs. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 220**:** 1483–1507

Anon (2018) Johnson: Crossrail project is costing £600m more than initial budget. Railway Technology

Baxter G, Sommerville I (2011) Socio-technical systems: From design methods to systems engineering. Interacting with Computers 23**:** 4–17

Blanchard BS, Fabrycky WJ (2011) Systems Engineering and Analysis. Pearson.

Brandt E (2006) Designing exploratory design games: A framework for participation in participatory design? Proceedings of the 9th Participatory Design Conference, pp 57–66

Brandt E, Messeter J, Binder T (2008) Formatting design dialogues – games and participation. CoDesign 4**:** 51–64

Tim Brown T (2009) Change by Design. New York: HarperCollins Publishers.

Cai Y, Starly B, Cohen P, Lee YS (2017) Sensor data and information fusion to construct digital-twins virtual machine tools for cyber-physical manufacturing. Procedia Manufacturing 10: 1031–1042

Challenger R, Clegg CW, Robinson MA (2010) Understanding Crowd Behaviours, Volume 2: Supporting Evidence. Cabinet Office, London

Challenger R, Clegg CW, Shepherd C (2013) Function allocation in complex systems: reframing an old problem. Ergonomics, 56(7): 1051–1069

Checkland P (2000) Soft Systems Methodology: A thirty year retrospective, Systems Research and Behavioral Science 17**:** S11–S58

Checkland P, Holwell S (1997) Information, Systems and Information Systems: Making Sense of the Field. Wiley, London

Checkland P, Scholes (1999) Soft systems methodology: a 30-year retrospective. Wiley, London

Clegg CW (1979) The process of job redesign: Signposts from a theoretical orphanage? Human Relations 32(12): 999–1022
Clegg, C.W. (2000). Sociotechnical principles for system design. Applied Ergonomics 31, 463-477.
Clegg CW, Robinson MA, Davis MC, Bolton L, Pieniazek R, McKay A (2017) Applying organizational psychology as a design science: A method for predicting malfunctions in socio-technical systems (PreMiSTS). Design Science 3: e6
Clegg C, Shepherd C (2007) 'The biggest computer programme in the world… ever!': Time for a change in mindset? Journal of Information Technology 22(3): 212–221
Coleman R (ed), Hua Dong JCE (ed), Cassim J (ed) (2017) Design for Inclusivity: A Practical Guide to Accessible, Innovative and User-Centred Design (Design for Social Responsibility). Routledge, London
Conceicao C, Broberg O, Paravizo E, Jensen AR (2019) A four-step model for diagnosing knowledge transfer challenges from operations into engineering design. International Journal of Industrial Ergonomics 69**:** 163–172
Crowder RM, Robinson MA, Hughes HPN, Sim YW (2012) The development of an agent-based modeling framework for simulating engineering team work. IEEE Transactions on Systems, Man, and Cybernetics – Part A: Systems and Humans 42(6): 1425–1439
Davis MC, Challenger R, Jayewardene DNW, Clegg CW (2014) Advancing socio-technical systems thinking: A call for bravery. Applied Ergonomics, 45: 171 –180
DeChurch LA, Mesmer-Magnus JR (2010) Measuring shared team mental models: A meta-analysis. Group dynamics: Theory, Research, and Practice 14(1): 1–14
Dixon A, Liu Y, Setchi R (2016) Computer-aided ethnography in engineering design. Proceedings of the ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, August 21–24
Dorst K (2015a) Frame Innovation: Create New Thinking by Design. The MIT Press.
Dorst, K. (2015b). Frame creation and design in the expanded field. The Journal of Design, Economics, and Innovation 1, 22-33.
Drain A, Shekar A, Grigg N (2018) Insights, solutions and empowerment: A framework for evaluating participatory design. CoDesign: 1–21
Elliot C (Ed), Deasley P (Ed) (2007) RAEng: Creating systems that work. The Royal Academy of Engineering, London.
Elliot J (2018) Works Information Study (Supply Chain Quality Requirements) [Online]. Crossrail Learning Legacy. Available at: https://learninglegacy.crossrail.co.uk/documents/supply-chain-quality-requirements/ [Accessed 28th October 2019]
Fairley RE, Thayer RH (1997) The concept of operations: The bridge from operational requirements to technical specifications. Annals of Software Engineering 3: 417–432
Farrell R, Hooker C (2013) Design, science and wicked problems. Design Studies 34**:** 681–705
Favero PSH, Theuinssen E (2018) With the smartphone as field assistant: Designing, making, and testing EthnoAlly, a multimodal tool for conducting serendipitous ethnography in a multisensory world. American Anthropologist 120(1): 163–167
Fine CH (1999). Clock speed: Winning Industry Control in the Age of Temporary Advantage. Pursues Books, New York
Geerts D, Nouwen M, Van Beek E, Slegers K, Miranda FC, Bleumers L (2018) Using the SGDA framework to design and evaluate research games. Simulation & Gaming 50(3)**:** 272–301
Grant RM (2013) The development of knowledge management in the oil and gas industry. Universia Business Review 40: 92–125
Hamzah I, Nordin AL, Alias H, Rasid N, Baharin H (2018) Game design requirements through ethnography amongst pediatric cancer patients. Advanced Science Letters 24(3): 1567–1570
Harrison L, Earl C, Eckert C (2015) Exploratory making: Shape, structure and motion. Design Studies 41**:** 51–78

Hekkert P, van Dijk M (2016) VIP Vision in Design: A Guidebook for Innovators. Laurence King Publishing.

Hofstede GJ, De Caluwé L, Peters V (2010) Why simulation games work – In search of the active substance: A synthesis. Simulation & Gaming 41(6): 824–843

Hughes HPN, Clegg CW, Bolton LE, Machon LC (2017) Systems scenarios: A tool for facilitating the socio-technical design of work systems. Ergonomics 60**:** 1319–1335

Hull E, Jackson K, Dick J (2011) Requirements Engineering. Springer, London

IDEO (2020) [online] History. Available at: <https://designthinking.ideo.com/history> [Accessed 16 October 2020].

IDEO (2020) [online] Design Thinking Defined. Available at: <https://designthinking.ideo.com/> [Accessed 16 October 2020].

Jun GT, Canham A, Altuna-Palacios A, Ward JR, Bhrama R, Rogers S, Dutt A, Shah P (2018) A participatory systems approach to design for safer integrated medicine management. Ergonomics 6**:** 48–68

Karsh BT, Waterson P, Holden RJ (2014) Crossing levels in systems ergonomics: A framework to support 'mesoergonomic' inquiry. Applied Ergonomics 45**:** 45–54

Kundu S, McKay A, Baker RB, De Pennington A, Thorpe R (2012) Co-creating value across supply networks: Towards an agenda for supply chain design engineering capability development. Cambridge International Manufacturing Symposium: Capturing Value in International Manufacturing and Supply Networks – new models for a changing world. Møller Centre, Cambridge.

Larsen J (2017) Bicycle parking and locking: Ethnography of designs and practices. Mobilities 12(1): 53–75

Lewrick L, Link P, Leifer L (2018) The Design Thinking Playbook. John Wiley & Sons, Hoboken NJ.

Mabogunje A, Sonalkar N, Leifer L (2016) Design thinking: A new foundational science for engineering. International Journal of Engineering Education 32**:** 1540–1556

Maier A, Eppinger SD (2019) Responsible Design: Recognising the Impact of How We Design. Keynote lecture at International Conference of Engineering Design 2019, Delft, Netherlands. Available at: https://www.iced19.org/keynotes/responsible-design-recognising-the-impact-of-how-we-design/. Accessed on 19 October 2020.

McDonald KJ (2015) Beyond Requirements: Analysis with an Agile Mindset (Agile Software Development). Addison-Wesley Professional

McKay A, Baker RB, Kundu S, De Pennington A, Thorpe R (2013) Realising design engineering capability across distributed enterprise networks. Proceedings of the Ninth International Symposium on Global Manufacturing and China, pp 111–116

McKay A, Davis M, Hughes H, Pieniazek R, Robinson M (2020) Designing socio-technical systems: A multi-team systems case study. In Metcalf G, Kijima K (eds) Handbook of Systems Science. Springer, Tokyo, Japan

McKay A, Raffo D, Trowsdale DB (2008) Sustainable Product Design: From delivering sustainable products to enabling sustainable lifestyles. In Cipolla C, Peruccio PP (eds) Changing the Change: Design, Visions, Proposals and Tools, pp 1031–1039

Nemeth. (2004). Human factors methods for design: Making systems human-centered. CRC Press, London

Norman DA (1986) The Design of Everyday Things. Basic Books, New York

Olechowski AL, Eppinger SD, Joglekar N, Tomaschek K. (2020) Technology readiness levels: Shortcomings and improvement opportunities. Systems Engineering, 23(4): 395– 408.

Pahl G, Beitz W, Feldhusen J (2006) Engineering Design: A Systematic Approach. Springer, London

Pugh S (1990) Total Design: Integrated Methods for Successful Product Engineering. Prentice Hall.

Read GJM, Salmon PM, Goode N, Lenné MG (2018) A sociotechnical design toolkit for bridging the gap between systems-based analyses and system design. Human Factors and Ergonomics in Manufacturing and Service Industries 28**:** 327–341

Robertson T, Simonsen J (2018) Particiatory design: An introduction. In Simonson J, Robertson T (eds) Routledge International Handbook of Participatory Design. Routledge, London, pp 1-17

Robinson MA, Drury M (2020) How analysis engineers spend their time. NAFEMS Benchmark, January, 46–51

Robinson MA, Sparrow PR, Clegg C, Birdi K (2005) Design engineering competencies: Future requirements and predicted changes in the forthcoming decade. Design Studies 26(2): 123–153

Schuler DE (ed), Namioka AE (ed) (1993) Participatory Design: Principles and Practices. Lawrence Erlbaum Associates, Hillsdale New Jersey

Tao F, Qi Q, Liu A, Kusiak A (2018) Data-driven smart manufacturing. Journal of Manufacturing Systems 48: 157–169

Thaler RH, Sunstein CR (2009) Nudge: Improving Decisions About Health, Wealth and Happiness. Penguin Books.

Tromp N, Hekkert P (2019) Designing for Society: Products and Services for a Better World. Bloomsbury, London.

Ulrich, K. and Eppinger, S., Product Design and Development, McGraw-Hill, 2004.

United Nations (2020) [online] The 17 goals. Available at: https://sdgs.un.org/goals [Accessed 19 October 2020]

Vermaas PE, Hekkert P, Manders-Huits N, Tromp N (2014) Methods for Design for Moral Values. In Van den Hoven J (ed) Handbook of Ethics, Values and Technological Design. Springer, Dordrecht, pp 1–19

Wikipedia (2020a) Technology readiness levels. Available at: https://en.wikipedia.org/wiki/Technology_readiness_level [Accessed 16 October 2020].

Wikipedia (2020b) Concept of operations. Available at: https://en.wikipedia.org/wiki/Concept_of_operations [Accessed 16 October 2020].

Wood AE, Mattson CA (2019) Quantifying the effects of various factors on the utility of design ethnography in the developing world. Research in Engineering Design 30: 317–338