The attention to sustainability impacts arising during the lifecycle of products is growing as industry wants to increase its contribution to a sustainable society. To do so, companies must find ways to navigate the complexity of the needs within the socio-ecological system in which they operate. In engineering design projects, the interpretation of needs into requirements is essential, as they represent the collective understanding of the design problem to be solved. Ideally, requirements are possible to verify and validate, which makes it challenging for industry to integrate socio-ecological considerations, often based on qualitative models, into requirements. Sustainability then tends not to be prioritized in trade-offs with traditionally identified requirements for engineering design.

A qualitative research approach within design research methodology framed a sequence of studies guided by the research question ‘How can requirements be utilized to support Sustainable Product Development?’ First, a research gap was identified from a literature review which indicated a lack of socio-ecological systems contextualization in the identification, as well as the traceability of sustainability criteria to integrate into requirements. Secondly, a conceptual model was established for how management of requirements can be improved to facilitate traceability, as well as how contextual socio-ecological systems perspective can be introduced in the selection of sustainability criteria for engineering design projects. For this purpose, the results from a multiple-case study based on semi-structured interviews with seven design and manufacturing companies was triangulated with findings of an in-depth literature analysis. Five key elements of management of sustainability in requirements were proposed in a profile model corresponding to different levels of sustainability maturity. A third study explored, based on literature and prototype causal loop diagramming, the potential of a group model building approach to enhance contextual understanding of strategically identified, i.e., company-tailored, sustainability criteria in relation to traditional requirements in early phases of the product innovation process. A final study investigated how a strategic sustainability perspective can be integrated with engineering design methods and value modelling to create a decision support for concept selection.

The studies together indicate that key constituents of good requirements, traceability and systems contextualization, can be achieved also for socio-ecological sustainability considerations. This requires organizational commitment and will be reflected in the design of the operational management system for their product innovation process. Following the proposed five key elements of sustainability integration in requirements, a company is expected to increase the organizational sustainability maturity, and hence its capability to contribute to a sustainability transition. This research also shows that there is a gap in current methods and tools for enhanced socio-ecological systems contextualization. The two last studies of this thesis give promising approaches of tools and methods to be further developed and analyzed, namely group model building, system analysis and value modelling.
Utilizing Requirements to Support Sustainable Product Development

Introductory Approaches for Strategic Sustainability Integration

Matilda Watz
Utilizing Requirements to Support Sustainable Product Development
Introductory Approaches for Strategic Sustainability Integration

Matilda Watz

Licentiate Dissertation in Strategic Sustainable Development

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SWEDEN
‘There’s no order in nothing, and I can’t find everything.’

Astrid Lindgren, Pippi Longstocking
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Writing this thesis has given me the opportunity to truly reflect over what the first two and half years of this PhD journey has meant to me. In the beginning of 2017, I asked myself what to do next. I didn’t ask when, where or how but a few months later I found myself in Karlskrona as a PhD student without the slightest clue of all new experiences and possibilities this would bring. But I couldn’t be more grateful. For my inspiring new colleagues, friendships, the huge number of new things I have learned, new role models, the places I would get to visit, and the students I have met, these are all just a few things. My world has grown.

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Karlskrona, December 2019
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Abstract
The attention to sustainability impacts arising during the lifecycle of products is growing as industry wants to increase its contribution to a sustainable society. To do so, companies must find ways to navigate the complexity of the needs within the socio-ecological system in which they operate. In engineering design projects, the interpretation of needs into requirements is essential, as they represent the collective understanding of the design problem to be solved. Ideally, requirements are possible to verify and validate, which makes it challenging for industry to integrate socio-ecological considerations, often based on qualitative models, into requirements. Sustainability then tends not to be prioritized in trade-offs with traditionally identified requirements for engineering design.

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The studies together indicate that key constituents of good requirements, traceability and systems contextualization, can be achieved also for socio-ecological sustainability considerations. This requires organizational commitment and will be reflected in the design of the operational management system for their product innovation process. Following the proposed five key elements of sustainability integration in requirements, a company is expected to increase the organizational sustainability maturity, and hence its capability to contribute to a sustainability transition. This research also shows that there is a gap in current methods and tools for enhanced socio-ecological systems contextualization. The two last studies of this thesis give promising approaches of tools and methods to be further developed and analyzed, namely group model building, system analysis and value modelling.

Keywords: Strategic sustainable development, sustainable product development, sustainable product design, sustainability integration, sustainability requirements management
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Thesis disposition
This thesis includes an introductory part and the following papers. The papers have been reformatted from their original publication to fit the format of the thesis, but the content is unchanged.

Paper A

Paper B

Paper C

Paper D

Related publications
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1 Introduction

'Now the cheap has become expensive' (Jägerhorn, 2019)

In April 2019, when I slowly started up the process of writing this thesis, Inger Jägerhorn had just written an opinion piece for the Swedish Think-tank ‘Global Utmaning’ [Global challenge]. As a representative for her generation, people born in the late 1930’s, she commented on their blissful unawareness of the negative impacts of their ever so welcomed new take-make-dispose consumption reality. A newfound rich access to resources and energy simplified so many things and improved the quality of life for many. Jägerhorn mentions technology leaps together with access to cheap energy and electricity, which enabled cheaper manufacturing of goods, such as plastics, that in turn added value to people’s lives. However, the future impacts, known as unintended consequences, could not be foreseen. Today, she continues, we need to pay back for the hidden costs we were spared from back then (Jägerhorn, 2019). Our sustainability challenges, such as global warming, ocean plastic waste, emissions of toxic and hazardous chemicals, species extinction, land degradation, etc., are all examples of such sub-optimizations which by nature are more complex to solve after they have occurred, than preventing them (Steffen et al., 2004). This phenomenon is in design science commonly known as the design paradox (Ullman, 1992). It tells us that costs of design changes increase with time, alongside the knowledge about the design problem. In sustainable design research it is also recognized, emphasizing that the largest share of a products’ lifecycle sustainability impact is determined in the earliest phases of concept development (Poudelet, 2012). Nevertheless, design decisions must at some point be made, despite the fact that future impacts of a design can never be modelled with a hundred percent certainty. Regardless whether the impacts cause positive or negative consequences from a sustainability perspective, or not.

Sustainable development is about design. Design, and hence, sustainable design, is about decision-making.

History of design and manufacturing, as well as current practice, shows us that sustainability considerations fall short in design decision-making. While it may be argued that sustainability should be considered as a value carrier, it is within design decision-making more often associated with cost. Institutions, policies and design methods available today are not designed to have the capability of promoting the ‘true value’ of sustainability but are, instead, programmed to generate profit in a linear business model (e.g. Daly, 2007). Sustainability impacts are, still, considered as externalities to the system which hinder industry to integrate a systemic and rigorous lifecycle sustainability perspective in their rationales for design decisions through traditional means (Broman and Robért, 2017). Long, complex value chains with multiple actors further complicate transparency and thus availability and accuracy of information about lifecycle sustainability impacts of design solutions (Manzini, 2007). Traditionally, design has therefore focused on, and mainly used information about, the design impacts that can be directly linked to cost-and value models which are internalized in the economic system. This is reflected in the common view of a product
lifecycle within industry. In their well-known book on Product Design and Development, Ulrich & Eppinger (2012) distinguish between the ‘product lifecycle’ and the ‘natural lifecycle’ of a design solution, where the first one encompasses raw material extraction, production, distribution and use, finalized by an end-of-life-solution scenario. The second solution encompasses the growth and decay of natural resources and spans over a much longer time period. Even though the authors acknowledge that product designers can influence the impacts of a design solution on the natural lifecycle through design decisions, they do not discuss how such decisions may be systematized.

A piece of the puzzle may therefore be the design of the product innovation process itself.

Increasing awareness of our currently unsustainable development has given rise to a global agenda to shift towards a sustainable development. To contribute to the transition needed into a state of sustainability, new design- and industrial production frameworks and approaches have emerged. Industrial ecology (Graedel, 1994), Clean Production (Jackson, 1993), Ecological design (Cowan and van der Ryn, 1996), Ecodesign (Brezet and Hemel, 1997), Biomimicry (Benyus, 1997), Circular Economy (e.g. Stahel, 2015), design for sustainability; design for the environment; design for circularity; etc., and sustainable design (Ceschin and Gazluluso, 2016) are examples of such approaches. Tools, methods and design strategies have been developed to guide designers and decision-makers in their innovation processes to develop products and systems that comply with the theoretical criteria of the above-mentioned frameworks and design approaches (Bovea, 2014). Unfortunately, it seems, they have been proven difficult to implement (Held et al., 2018); industry wants tools that are adaptable, easy to use and that are compatible with other design tools already in place (Ahmad and Wong, 2018). Many methods and tools, although they may have great potential, are difficult to learn how to use, time consuming and they often generate qualitative results with high uncertainties that are difficult to use in early stages of the product innovation process (Hallstedt, 2017). Using ambiguous figures and models does not comply with traditions and quality standards in the engineering environment, which may be exemplified with how The International Council on Systems Engineering, INCOSE (2015) defines a requirement; ‘A statement that identifies a system, product, or process characteristic or constraint, which is unambiguous, clear, unique, stand-alone (not grouped), and verifiable, and is deemed necessary for stakeholder acceptability’ (Walden et al., 2015). Not all organizations have the capability to manage the complexity associated with sustainability impacts in their design processes, and thus, currently available methods and tools for sustainable design might not be compatible with the capabilities of an organization (Pigosso et al., 2013). Previous research on capabilities for sustainable design, ecodesign and sustainability maturity alludes to the design of the decision- and management processes as a key to enable implementation of support tools and methods for sustainable design, see, e.g., Zhang and Zwolinsky (2017); Brones et al. (2017); Mendoza et al. (2017). Industry highlights the power of requirements but struggles to include a perspective on sustainability that is wider and more ambitious than what is required by legislation, market standards or specific customer demands, see, e.g., Nilsson, Sundin and Lindahl (2018); Silvius et al. (2017).
The background described above woke my interest in scrutinizing the role of the requirements management process, and by doing so I would hopefully arrive at a better understanding of whether the design of this process could be improved, and in that case how, to ease the implementation of sustainable product development.

1.1 Aim, scope and research questions

Having clarified the context in which the need for this research is identified, I formulated the aim of my licentiate thesis. Hence, the aim is articulated as to generate a deepened understanding about keys to implement a strategic sustainability perspective in the product innovation process, through the lens of requirements management. The scope within which my research has been conducted is the early phases of product innovation process in, mainly but not limited to, engineering design and manufacturing companies located in Sweden. Guided by the overarching question ‘How can requirements be utilized to support Sustainable Product Development?’, three research questions (RQs) were defined. RQ1 and RQ3 were furthermore specified into two, respectively one, sub-research questions. All RQs can be found in Figure 1.

![Figure 1. Research questions used in this thesis.](image)

1.2 Thesis structure

The remainder of the thesis consists of the following chapters. In chapter 2, I provide a theoretical background to my research topic. It provides the key terms and constructs which form the frame of reference which shapes the context of my thesis project. In chapter 3, the research design and methodological approach are described together with an epistemological and ontological reasoning based on the multidisciplinary research context to justify my philosophical stance that shaped and informed the chosen research approach. I also describe the actual methods applied as well as their relation to the research questions. Chapter 4 contains summaries of the four papers which together represent the research studies conducted during the
licentiate project, providing the results from the execution of the chosen research
design. In chapter 5, I discuss the findings in relation to the goal and research
questions and give a methodological reflection regarding the research quality. Main
contributions to academia and industry and directions for future research are also
discussed and suggested. In chapter 6, I consolidate the discussions into a conclusion.
Thereafter follow references and the appended papers, which have undergone slight
formatting to fit into the thesis format.
2 Sustainable design and product development research: a theoretical background

‘Artefacts have consequences, not agency’ (Hornborg, 2017)

The acceptance of sustainability as a science represents a major ontological shift, that is, way of seeing the world, in human society. In this worldview, humanity is understood and accepted as an agent capable of manipulating, i.e., engineering, the Earth systems, while also being an object under influence of the conditions of the very same system (Steffen et al., 2004). This means that human society can impact the earth systems, but the impacts in turn may cause other changes in the system behaviours to which society then must adapt. Human-made systems, i.e., social systems, are therefore inevitably interconnected with ‘ecological’ systems but are not per se valuable to sustain from an ecological systems perspective. The ecological systems sustain without humans, so to say. From a social systems perspective, however, there is an obvious value in a functioning ecological system, as it provides the basic conditions for our lives. Balance is also needed among social systems, as unbalance, on the contrary, not only causes threats to peoples’ right to their needs. Unbalanced social systems can also pose threats to ecological systems. Such threats occur, for instance, when ‘we’ cannot agree on who is entitled access to the resources provided by the ecological system (Bennet et al., 2015). Manipulating this balance to the degree that a systems’ resilience capacity, i.e., the system’s ability to adapt to changing conditions, is surpassed, will likely lead to system behaviour changes. These new behaviours cannot be predicted (Steffen et al., 2004). Sustainability as a science is therefore about the behaviours of the interconnected Earth systems, to which human society belongs and must adapt. By developing the understanding of the Earth systems for the purpose of long-term societal value, research on sustainability therefore spreads across all disciplines and is hence both multi- and transdisciplinary (Jerneck et al., 2010).

The ability to interfere and change the system conditions through industrial scale engineering design have given the industrial human society the power to act as a new geological force, agents in the socio-ecological system. Agents can deliberately challenge the system conditions, that is, designing or engineering with a purpose in mind, while artefacts are subject to and adapt to the system conditions they are given (Hornborg, 2017). Earth systems research calls this a shift from a phase of ecological balance, the Holocene, to a phase where the responsibility is in our hands, the Anthropocene (Steffen et al., 2011). Through the consequences of our engineering of artefacts, though well-intended, the balance of the earth systems has been challenged. Therefore, as we continue designing for our societies, we now need to adopt a systems perspective in the rationale for our decisions (Leach et al., 2012).

Some sustainability researchers focus on developing a better understanding of the socio-ecological system conditions and their behaviours, especially related to their resilience capacity. Being able to estimate the limits to which the systems can be pressured can provide us with indications of what type of impacts we must relieve the
socio-ecological systems from, and to which extent. This type of research has generated a common understanding of global sustainability challenges, reflected in for instance Rockström et al.’s Planetary Boundaries, in which information about the health of the ecological system connected to human activity is continuously updated (Rockström et al., 2009). The pressures on the ecological systems can in turn be extrapolated into issues in the social systems that threaten our possibility for a 'safe operating space for humanity'. The Sustainable Development Goals (SDGs) describe a visionary scenario for sustainable development that is well-known and used by both academia and industry, and it is based on the branch of sustainability research. Sustainability research focusing on the status of socio-ecological systems provides some guidance to the product innovation process; it indicates which impacts or emissions to the ecological system that should be reduced. But not how it should be done.

2.1 Framework for Strategic Sustainable Development

The weakness, from an engineering design perspective, with the above-mentioned research on sustainability, is that it does not support decision-making in complexity for system change. Rockström et al. (2009) describe this: ‘Although the planetary boundaries are described in terms of individual quantities and separate processes, the boundaries are tightly coupled. We do not have the luxury of concentrating our efforts on any one of them in isolation from the others. If one boundary is transgressed, then other boundaries are also under serious risk’. Aiming to overcome this challenge, another branch of sustainability research has operated from a root-cause level, defining principles for a balanced socio-ecological system scenario, and developing guidance for decision-making that can lead towards it. Such principles provide an opportunity to define the safe operating space, which takes place in the future, despite being limited in detail. Then, systemic activities that contribute to the sustainability challenges can be systematically identified so that actions can be strategic from a systems perspective. This is needed so that product designers, engineers, architects, infrastructure planners and policy makers can be guided to make decisions that lead towards a sustainability transition with reduced risk for sub-optimizations (Fiksel, 2006).

Against this background, I subscribe to the Framework for Strategic Sustainable Development (FSSD), which at a basic principle level defines which mechanisms to consider for breaking the behaviours in our engineered society that systematically cause degradation of the socio-ecological systems (Broman and Robért, 2017).

The FSSD encompasses five levels, called the Five Level Framework for Planning in Complexity (FLF), see Figure 2. At the Systems level, the sustainability challenge is recognized as a systems error, in which we, the humans in the society, are causing a systematic degradation of the Earth’s socio-ecological systems. The resilience capacity of the socio-ecological system is the boundary conditions which must be respected to avoid forcing the Earth systems beyond a tipping point, after which a new balance, i.e., with new system conditions, will be established. As we cannot predict the behaviour of a socio-ecological system operating under these new conditions, the aim is to maintain a balanced system, a safe operating space. A plan for a transition to such
a state requires that the state itself must be defined. Therefore, while acknowledging the hierarchical relationship, interconnectedness and complexity of the socio-ecological systems, eight sustainability principles (SPs) can be used, constituting the success level. Based on natural and social sciences, the eight SPs describe the basic conditions in which the socio-ecological system can be in balance, and thus sustainable without declaring details of a specific scenario. The strategic level contains guidelines to follow when designing a plan towards the vision, based on backcasting and the concepts of flexible platforms. At the actions level, concrete activities according to the strategy, i.e. how to implement the plan, take place. The operational management system of a product developing organization, and its subsequent requirement management system, is an example of an implementation platform for such a strategy. To support selection of strategies, assessment and evaluation, tools and methods can be used. These are organized into the tools level. The SPs, combined with systems thinking and backcasting, provide a platform for shared envisioning and assessment, i.e., the conditions of a scenario, to ensure a sustainable development towards such a state (Broman and Robért, 2017).

Figure 2. The Five Level Framework for Planning in Complex Systems (FLF).

I position the scope of this thesis, namely, early requirement management processes for engineering design projects, between the strategic guidance- and actions level of the FLF. Therefore, I have mainly used the system- and success levels of the FLF to inform my studies as a theoretical reference. Hence, this thesis investigates to which extent the strategic guidance level of organizations, and specifically requirements management processes, currently adopt a strategic sustainability perspective as means to implement SPD. The two levels are also used in a prescriptive manner, i.e., by suggesting how requirement management could be designed to better support selection of actions, and, consequently, methods and tools that can give guidance towards organizational sustainability maturity and product sustainability.
A nested model of the Earth’s socio-ecological systems illustrates the interdependencies between the systems. The outer boundary is the ecological system. Without this system, which includes all subsystems including the lithosphere, biosphere, atmosphere, troposphere, etc., there is no operating space for societies at all. Societies are utterly dependent on the existence and balance of the ecological system, although capable of distributing and changing its components in such a way that their balance, and their adaptive capacity, can be trespassed. The difficulty in predictions of consequences is a challenge with complex adaptive systems; well-intended actions may still lead to negative impacts (Bennet et al, 2015). At the same time, also societies are also constituted by complex adaptive systems. To be balanced social systems require trust, diversity, self-organization, learning and common meaning between their components, i.e., individuals, institutions and corporations. A sustainable society can therefore not, systematically, be exposed to obstacles that undermine these components (Missimer, 2015). As the economy is a societal institution in which the market provides the operating conditions to businesses, companies that truly contribute to a sustainability transition must, hence, operate in a way that complies with principles for balanced socio-ecological systems (Raworth, 2012). The SPs of the FSSD subscribe to these interdependencies and are based on science on socio-ecological system science and are presented in Figure 3.

2.2 Sustainable Product Development

Sustainable Product Development (SPD) is a practice and field of research that has emerged as a result of our increasing awareness and understanding about the impacts that our socio-technical processes cause in society and in the environment (Hallstedt and Isaksson, 2017). In parallel, the linear economic model is increasingly acknowledged as the driver behind the negative socio-ecological impacts. Historically, and today still, the economy allows industry to externalize negative effects of the socio-ecological system. As a result of the increasing awareness, policy makers continuously sharpen regulations that force industry to increase their responsibility (Schulte and Hallstedt, 2017). Corporate sustainability initiatives such as Cleaner Production (UNEP, 2007), the Ecodesign directive for energy-related products
(Directive 2009/125/EC, 2009), the International Organization for Standardisation (ISO) standards for occupational health and safety (ISO 45001:2018, 2018), organizational environmental management (ISO 14001:2015, 2015), and environmental lifecycle assessment (ISO 14044:2006, 2006) are all examples of how industry collaborates with policy instances to create certification opportunities which can be used to prove commitment to, and work systematically towards, more sustainable operations. These standard certifications can in turn create a ripple effect on the market, where competitors feel a need to follow. Other examples are committing to global frameworks such as the ten principles of the UN Global Compact, and in that, the Sustainable Development Goals (UN, 2014). A variety of sustainable design strategies, as well as methods and tools, have been developed to support design of products and services that contribute to the development of, or even fit into, a sustainable society. Design- and manufacturing strategies such as Industrial Ecology, Cradle-to-cradle, or Biomimicry all aim to mimic behaviours of natural ecosystems. Examples include circular economy and industrial symbiosis networks that aim to connect material- and energy flows to minimize waste, or the use of honeycomb structures for minimized structure weights in load-carrying structures (Cohen-Rosenthal, 2000). The interest in Product Service Systems (PSS) and Integrated Product-Service Offerings has also grown remarkably due to their potential for resource efficiency and for including a wide stakeholder perspective, e.g., (Tukker et al., 2004; França et al., 2017). Designing on a system level rather than for incremental improvement is what distinguishes 'strong sustainability' from 'weak' (Dietz and Neumayer, 2007), or 'high sustainability maturity' from 'low' (e.g. Gaziliusoy, 2015). Although gathered under the umbrella term, ‘Design for Sustainability’, neither of the above-mentioned sustainable design strategies are, unfortunately, intrinsically sustainable (Ceschin and Gaziliusoy, 2016). A design strategy that focuses on optimizing a parameter in only one sustainability dimension, i.e., social, ecological or economic, might in fact cause negative impacts in another. These impacts can be called unintended consequences, or sub-optimizations (Hjort and Bagheri, 2006; Laurenti, 2016).

Research in the fields of Sustainable Design, Design for Sustainability, and SPD, acknowledge the importance of systems design and discusses how it could be achieved, but industry seems to lag behind. In fact, even tools for incremental sustainability improvement have been proven difficult to implement in organizational processes for product design and innovation (Ahmad and Wong, 2018). From what it seems, they fall short in terms of usability as they are perceived as being time-consuming and difficult to learn how to use (Held et al., 2017). A plethora of tools now exist both for analysis of sustainability performance, the most widely known being Lifecycle assessment, for ideation in terms of sustainable design strategies, e.g., ecodesign and biomimicry, and integrated product development tools for concept generation and selection (Bovea, 2014). However, acknowledging the risk for unintended consequences from lack of a systems perspective during sustainability assessment and concept selection between designs, the field of Sustainable Product Development (SPD) has emerged, which adopts a scope of sustainability that encompasses a socio-ecological systems perspective (Gangnon et al., 2012). SPD
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furthermore subscribes to the principle-based definition of sustainability and strategic approach to sustainable development defined in the FSSD, described by Hallstedt and Isaksson (2017) as when a ‘strategic sustainability perspective is integrated and implemented into the early phases of the product innovation process, including life-cycle thinking’. Research in the field of SPD consequently aims to enhance capabilities in organizations for designing and developing products, or PSS solutions, that fit into or contribute to a sustainable society. That is, developing an improved understanding of sustainability within the organization, as well as designing methods, tools and processes that can be implemented and used without risking the ability to sustain on the market. Then, designers can become the agents that, through the creation of artefacts, support the transition to sustainability, instead of causing negative unintended consequences (Manzini, 2007).
3 Research design and methodology

‘Essentially, all models are wrong. Some are useful’ (Box, 1976)

In the first of the following sections, 3.1., I have placed a reflection on my philosophical stance, upon which I in section 3.2 build the approach to a research design. Thereafter, in section 3.3., I describe the methods applied in this thesis within the frame of that design. The last section of this chapter, 3.4, presents the criteria which were used to select the research design, and which will be used later in the thesis to assess the research quality.

3.1 Reflections on axiology, ontology and epistemology

Decisions must be well-informed from a sustainability perspective so that needs of today can be satisfied with a minimized risk of reducing the ability of our own generations, or others, to meet their needs in the future (Brundtland, et al., 1987). Achieving a sustainable development requires careful design of institutions, policies and technologies, engineering design solutions included, that can meet these needs. Uninformed engineering design decisions can lead to problematic consequences such as the sustainability challenges we are facing today. The desire to achieve change in our relationship to the socio-ecological system therefore makes sustainability science engineering design-oriented (Miller et al., 2011) and research in sustainable design is concerned with (at least) two of core questions for sustainability, namely, ‘mapping and deliberating sustainability values’ and ‘exploring and fostering socio-technical change’ (Miller et al., 2014). Coming back to the design paradox, support methods and tools for sustainable design decisions in early phases of the product innovation process should allow this rigorous sustainability perspective as it allows for larger design freedom and less risk for costly sub-optimizations (Ullman, 1992; Poudelet, 2014).

With this background I take a positivist-constructivist stance in this thesis, as it mainly searches for answers to how, rather than if, systems, processes and methods can be developed to solve a problem (Karlsson, 2009). This solution-oriented stance makes the basic assumption that answers can be found for a given design research phenomena. Together with a lens of critical realism, this stance can be taken also in research for sustainability, as it calls for interdisciplinarity (Høyer and Naess, 2008). This entails subscribing to an Earth system ontology in which we, the human kind, acknowledge and respect our dependency as well as the ability to impact the state of the socio-ecological system (Cohen-Rosenthal, 2002). Not only are humans able to architect it, as in a post-modern worldview; the complexity of the Earth systems structure and potential to maintain balance and adaption capacity, i.e., the potential to change given new conditions, is also appreciated. Hence, manipulation of the socio-ecological system may cause new system conditions to which humankind must adapt. How and when these conditions will appear is impossible to predict. That is why a sustainable societal development aims to maintain the current system conditions, i.e., the balanced geological conditions known as the Holocene (Rockström et al, 2009). This is also the underlying rationale for adopting a principle-based definition of
sustainability, as it allows agile planning and measuring as detailed characteristics of the sustainability scenario remain unknown (Broman and Robért, 2017).

If the purpose of SPD is to improve design processes and methods so that solutions can fit into sustainability constraints, e.g., provided by sustainability principles, or contribute to society’s transition to such a state, then a design research methodology (DRM) (Blessing and Chakrabarti, 2009) becomes a natural approach to the challenge. Methods therefore need to be selected and applied in such a way that new knowledge is generated and from which new ideas can emerge, and whether these be qualitative or quantitative, depends on the scope and context of the research questions (Creswell, 2014).

### 3.2 A qualitative design research methodology approach for sustainable product development

Design research was recognized as a scientific field in the 1960’s. It considers operations, here understood as systematized processes for designing and manufacturing, or other technical processes, and the management of these. Emerging from a need and desire to first understand design processes and methods, it then aims to improve these in a generalizable rather than domain-specific way. Gibbons et al. (2010) call this research for the ‘new knowledge production’ for ‘Mode-2’ science, which is knowledge created in research projects emerging from multi-disciplinary needs. Therefore, it adopts the scientific method as means for this purpose. In Wikipedia, science is described as ‘a systematic enterprise that builds and organizes knowledge in the form of testable explanations and predictions about the universe’ (Wikipedia contributors, 2019), leading to the implication that new knowledge about design must be created in a repeatable, verifiable and validatable way for it to be generically applicable. Good research quality can then be recognized as research that is valid in the intended context, and in that reliable and credible.

In the light of this background, I aimed to create a good research design through the application of a sequence of qualitative research methods.

While design research is process-flow oriented, much like design projects, qualitative research offers a more flexible and interactive approach. A research design based on qualitative methods, although influenced by the structure of the DRM framework, was selected as a suitable approach. DRM is supposed to provide understanding and support to improve design research, that in turn can provide knowledge and support to improve design practice and design education (Blessing and Chakrabarti, 2009). As design research can be conducted using qualitative methods, I introduce the interactive model for qualitative research as described in Maxwell (2012) as the main influence for the development of my research design. Five essential components constitute the interactive model using the research questions as the central focus, while the other four components, i.e., goals, conceptual framework, methods and validity are interconnected but must not be conducted in a certain order. Qualitative research design processes can therefore be agile. The methods applied in this thesis are
described in the subsections. An overview of the research design development can be found in Figure 4.

Figure 4. A qualitative design research methodology, adopted from the interactive model for qualitative research (Maxwell, 2012) and the Design Research Methodology framework (Blessing and Chakrabarti, 2009).

Aiming to contribute to new knowledge by establishing a model for understanding the role and potential of using requirements management as a means for SPD, a natural first step was to establish what it is we do not know about this already. A knowledge gap can be identified in different ways, but normally, and in the case of my thesis, a literature analysis, based on a systematic review process (SLR), was used. This phase constituted my research clarification (RC). Having a better picture of the current state of knowledge in academia, my research questions could be refined, after which a second study was conducted aiming for a deeper understanding of theory and the state of practice in industry. An in-depth literature review and a multiple-case study constituted the main methods in this first descriptive study (DS1). The DS1 provided answers to ‘what is going on’, rather than ‘why does this need to be investigated’ as the SLR indicated. The third, prescriptive study (PS1) proposes an approach to ‘how it can be changed’, which is the natural continuation of any design project, or research project driven by a purpose to transform a current situation to a better one. How the developed prescriptive approach can be evaluated is usually described in a second descriptive study (DS2) and is in this thesis only initiated. This setup is by the DRM framework recognized as a comprehensive, study-based, development of design support (Blessing and Chakrabarti, 2009), of which more details are shown in Table 1. Therefore, the selected combination of methods for the research design should represent the declared research philosophy, i.e., positivist-constructivist: Hence, the methods should have allowed me to start with a constructive and explanatory sequence of studies of the research problem which moved into a positivist approach that explores strategies to transform the problem into a desired state (Voss, 2009).
Table 1. A qualitative research design following the structure for a comprehensive study-based support development (Blessing and Chakrabarti, 2009).

<table>
<thead>
<tr>
<th>Phase</th>
<th>Means</th>
<th>Type</th>
<th>Main contribution</th>
<th>Nature of RQ’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC</td>
<td>Literature analysis</td>
<td>Review</td>
<td>Goals and research questions (Reference model)</td>
<td>Why?</td>
</tr>
<tr>
<td>DS1</td>
<td>Empirical data analysis</td>
<td>Comprehensive</td>
<td>Conceptual framework (Initial impact model)</td>
<td>What?</td>
</tr>
<tr>
<td>PS</td>
<td>Assessment, experiments, prototyping, synthesis</td>
<td>Comprehensive</td>
<td>Support and evaluation criteria (Impact model)</td>
<td>How?</td>
</tr>
<tr>
<td>DS2</td>
<td>Empirical data analysis</td>
<td>Initial</td>
<td>Evaluation Methods and results validity</td>
<td></td>
</tr>
</tbody>
</table>

3.3 Qualitative methods used in this thesis

Although the DRM framework, which adopts a linear research process, influenced the formulation of my research questions some of the studies overlapped each other. This reflects the qualitative approach which I applied and allowed research questions to be refined continuously throughout the thesis project while guided by the overarching research goal. The methods could be selected accordingly and are described in the following subsections.

3.3.1 Literature reviews

Several types of literature reviews were used in this thesis. The project started with a conceptual literature review (Thomas and Hodges, 2010), based on a snowball sampling approach (Wohlin, 2014), from which I gained an overview of the field of research on sustainable product development and sustainable design. Thereafter followed a review of purposefully sampled publications (Palinkas et al., 2015), and the result of these two steps was a record of key words, terms, constructs as well as key publications and their publication years. I also visualized the connections between key publications and conducted a frequency analysis of the key words, as an initial conceptual framework (Maxwell, 2012) or reference model (Blessing and Chakrabarti,
which is the term I will continue to use. The reference model helped me scope
the search inquiry for my systematic literature review as well as selection, classification-
and categorization criteria for the review, according to the guidelines for structured
literature reviews in Croom (2009). The systematic literature review consisted of the
following elements: i) selection of databases and criteria for selection, classification
and categorization; ii) search inquiry formulation; iii) search for publications; iv) title
and abstract screening; v) full paper read; vi) classification and categorization of
selected papers. Details of the systematic literature review process, and the results, can
be found in Paper A. The conclusions from the literature reviews were used as an
input to the continuation of the thorough descriptive phase of the research, which
was constituted by an in-depth literature review combined with a multiple case study.

The approach for my in-depth literature review was based purely on purposeful
sampling. This choice was made after I had revisited my reference model and
overarching research goal, realizing that I needed a stronger theoretical framing of the
desired state. With the purpose of establishing a more robust foundation of terms and
constructs and thus enable a stronger conceptualization of the findings of the parallel
multiple-case study, I turned to key publications in the field of product design and
systems engineering for design, and sustainable design. Therefore, the literature review
came to include recent publications that address sustainability in product design
project management, and that define sustainability maturity for a product developing-
and manufacturing organization. To gain a deeper understanding of key elements of
requirement management, I went back in time to dive into design literature using
snowball sampling. In this way, I aimed to clarify the research context of my
descriptive study, i.e., to build a bridge between design research, project management
and sustainability research. The conceptual framework, consisting of key terms and
constructs for requirements management in product design and sustainability
maturity, helped me categorize the themes found in the multiple-case study. The
findings from both studies were triangulated as a novel model and are presented in
Paper B.

Snowball sampling of key publications was also used in Paper C and Paper D, which
are two examples of exploratory studies for the purpose of prescriptive method
development. Like in Paper B, the aim was to bring insights from different research
fields, but to generate ideas for future research directions rather than establishing a
frame of reference. The literature analysis in Paper D is the only study in which non-
academic publications was used in this thesis. This is motivated by the novelty of the
proposed research approach and the lack of available data in peer-reviewed
publications (Croom, 2009).

3.3.2 Multiple-case study

Although case studies generally are used for theory testing, they can in qualitative
research also be successfully used for theory building (Eisenhardt, 1989). Industrial
case studies are, for instance, useful when the purpose of the research is to gain better
understanding of the ‘real world’, i.e., ‘new’ knowledge that requires collection of
empirical data (Voss, 2009). I decided to use a multiple-case study first as a means for
refining the reference model which was the result of the literature reviews, hence in a constructive manner, as well as testing it to exemplify how the model could be used in practice, adopting a positivist mindset. However, a case study is not a method on its own, but a methodology which requires both data collection, analysis and synthesis. Hence, a combination of data collection methods and analysis methods was selected based on its potential of providing qualitative answers to the research questions. Likewise, the selection of case study participants needed to be considered.

The case selection was based on a combination of purposeful and opportunistic sampling and was therefore adopted to select case companies, desktop material and interviewees (Palinkas et al., 2015). The sampling approach was adopted due to the aim of achieving both external and internal validity of the results, which in case study research requires a balance between the amount of company cases as well as interviewees together with the level of detail in the questions included in the inquiry (Maxwell, 2012). In total, seven companies and fifteen interviewees participated. Semi-structured interviews and document analyses were used to collect empirical data. Two iterations of thematic coding, open- and structured-, i.e., of each interview and of each case report, then constituted the analysis of the collected material. This combination was adopted as the aim of the study was to establish a conceptual framework of generalizable themes, patterns and differences. Such a framework meets criteria for both internal and external validity and should hence be based on information from companies of different sizes and industries (Forza, 2009). The resulting cross-case analysis report outlined answers to the interview questions and gave insights to challenges and opportunities in requirement management processes related to sustainability integration in product development processes. These insights were together with the findings in the literature reviews conceptualized into five key elements of early requirements management for supporting organizational sustainability maturity. These constitute the basis for a profile model for management of sustainability integration in engineering design requirements which is proposed in Paper B, in which a more comprehensive description of each phase in the multiple-case study can be found. Figure 5 shows an overview of selected methods for data collection and analysis and how they were applied.

![Figure 5. Overview of the multiple-case study. The abbreviations are: CX = Case X, IX = Interviewee X, CRX = Case report X. An asterisk (*) indicates that document analysis material was collected.](image-url)
3.3.3 Prescriptive design method development

Based on the findings in literature and in the multiple-case study, I moved on to a prescriptive phase. Here, the purpose was to explore and develop a prescriptive methodological approach suitable to support organizations in achieving the key elements that emerged from the descriptive multiple-case study, and consequently the research gap identified in literature. This approach corresponds to the objectives of a prescriptive study as described in Blessing and Chakrabarti (2009), namely, to i) identify the most useful actions to improve the current situation, ii) to describe the expected outcome of doing these actions, iii) to select and describe how to measure whether the action was useful for its intended purpose, iv) to develop support for the design process so that the actions can be systematically implemented in the design process, and v) to evaluate whether the support is useful for its intended purpose. In this thesis, the prescriptive study was mainly focused on the first three steps, i-iii, of which there are elements in all papers but mainly in paper B and C. Paper D, and to some extent Paper C, present a prescriptive illustrative case study. A sequence of design methods is proposed as decision support for early concept selection, thus covering step i-iv.

Several methods can be used to both describe the objectives and requirements which the developed method should meet, and for inspiration to the new support development. Hence, the literature reviews and the multiple-case study in Paper A and B contribute with objectives and requirements for a potential new design support. Paper C and Paper D are examples of developed prescriptive design approaches, where specific methods and tools are proposed to be used according to the developed methodology to improve the design process. Paper C suggests that group model building with causal loop diagrams is used in the earliest phases of the requirements management process. Paper D proposes that the conceptual development phase is supported by a sequenced application of design methods, namely, platform-based product design using CC-modelling (Claesson, 2006), a strategic sustainability analysis using Sustainability Lifecycle Assessment2.0 (Villamil et al., 2018) as input to a value-chain impact analysis where Value Modelling according to the concept screening matrix approach (Ulrich and Eppinger, 2012) was applied. Details of the proposed approaches and frameworks are described in respective paper, and an overview of the methods as well as their contribution to each research question are presented in Table 2.
Table 2. Overview of research design phase, research questions, methods, results and papers.

<table>
<thead>
<tr>
<th>Main RQ</th>
<th>Sub-RQs</th>
<th>Phase (means)</th>
<th>Methods</th>
<th>Outcome</th>
<th>Paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>How can requirements be utilized to support SPD?</td>
<td>1. How can sustainability be integrated in requirements?</td>
<td>Research Clarification</td>
<td>Literature Reviews</td>
<td>Research gap Reference model</td>
<td>A (B)</td>
</tr>
<tr>
<td></td>
<td>1.1. What methods are used to integrate sustainability aspects in requirements?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.2. How are sustainability criteria and indicators identified?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. What are sustainability requirements and how are they identified and managed in design projects?</td>
<td>Descriptive study</td>
<td>Literature review Multiple-case study Semi-structured interviews Document analysis Thematic analysis</td>
<td>Refined reference model; key elements and desired situation</td>
<td>B (A)</td>
</tr>
<tr>
<td></td>
<td>3. How do you guide concept development and selection from a sustainability and value perspective?</td>
<td>Exploratory and Prescriptive study</td>
<td>Literature review Illustrative case study</td>
<td>Proposed methodological approach</td>
<td>D (B)</td>
</tr>
<tr>
<td></td>
<td>3.1. How can sustainability criteria be related to design requirements, using a systems perspective?</td>
<td>Exploratory and Prescriptive study</td>
<td>Literature review Illustrative case study</td>
<td>Proposed method, research direction</td>
<td>C (B)</td>
</tr>
</tbody>
</table>

3.4 Quality criteria for developed research design

Research can be useful without following standards for academic research quality. Arguing that the results of a study contribute to an academic field of research induces the requirement to adopt the scientific method, and how well that is done determines the quality of the research. So how can research quality be assured? Corbin and Strauss (2008) propose ten criteria as the basis for a general quality evaluation, namely, fit, applicability, concepts, contextualization, logic, depth, variation, creativity, sensitivity, and evidence of memos. The central quality element for qualitative research is validity, i.e., the context in which the results can be considered ‘true’, and reliable, that is, the trustworthiness of the methods and the application of these in relation to the research goal and questions (Creswell, 2014). Maxwell (2012) describes validity in terms of ‘correctness’ and ‘credibility’, which may refer to what can be recognized as internal-, respectively external validity. Internal results validity concerns the truthfulness of the results within the context from which they were generated, while external validity may concern the generalizability of the results outside that scope, that is, how applicable the results are in a wider context if this is the goal of the research, and, hence, how credible the results.
are. The trustworthiness of a qualitative research study is generally discussed in terms of replicability (Creswell, 2014). Replicability, then, concerns the internal validity and refers back to what Corbin and Strauss call ‘evidence of memos’, i.e., how possible it is for someone else to repeat the same study with similar results based on the documentation of the study. In addition to the two above-mentioned dimensions of validity, Croom (2009) describes another four, namely, construct-, descriptive-, interpretive-, and theoretical validity. These dimensions of validity can be described in terms of how clear and understandable the developed constructs are both for the intended audience and the sources upon which the constructs are based. Such factors are, e.g., the replicability of the study, how well-accepted the results analysis is by the participants, respectively how reasonable the results are in relation to the nature of collected data. To claim that a study answers to all these aspects of qualitative validity, Creswell (2014) suggests the following eight strategies;

- **Triangulation**, coherency of themes that emerge from a variety of sources motivates the trustworthiness of findings.
- **Member-checking**, participants can be asked to comment on the accuracy of findings.
- **Rich description of findings**, inviting the readers to thoroughly understand the research context can make the results more realistic.
- **Clarify bias**, sharing reflections around the researchers’ background and interests’ potential weaknesses can be discussed openly.
- **Present negative results or discrepant information**, as sharing also contradictory evidence allows results to become realistic.
- **Prolonged research field time**, more experience with study participants and context enhances accuracy of findings as it increases the chance for saturation.
- **Peer debriefing**, involving another person that can ask critical questions about the findings provides a quality filter.
- **External audit**, similar to the previous strategy but with even less risk for bias.

In short, these strategies suggest that findings should be reasonable from both an academic and practical perspective, while providing some new insights that are substantial and explanatory. The findings should also make sense, have the potential to make a change, consider different perspectives, be novel, un-biased and well-documented. Essentially, the quality of research boils down to that ‘so much depends upon who is doing the research, its purpose, and the method that is used’ as Corbin and Strauss (2008) explain. Threats to validity, hence, concern the researchers’ ability to identify their own biases, as well as their reactivity or influence on the results, i.e., how aware the researchers are of how the research design itself affects the outcome.

Attempting to avoid these threats, I used the above-mentioned eight strategies during the design of the research approach. How well they were applied will be discussed in chapter 4.
Matilda Watz
Utilizing requirements to support sustainable product development

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4 Summary of appended papers

This chapter presents a description of the four papers which I used to answer the research questions. In paper A, B, and C, I am the main author since I was responsible for the major share of all work. My co-author in these papers, my main supervisor Sophie I. Hallstedt, contributed as support during the design and execution of the research studies, as well as during the writing process of the paper. In paper D, I was the first co-author and contributed with the design and application of the sustainability assessment method which contributes to the combined method that the paper presents. The highly collaborative writing process was led by the main author Maria Siiskonen.

Table 3. How each paper contributed to each research question, and by which means. 'X' symbolizes a strong contribution while '(x)' refers to a partial contribution.

<table>
<thead>
<tr>
<th>Paper</th>
<th>RQ 1</th>
<th>RQ 2</th>
<th>RQ 3</th>
<th>Type of study</th>
<th>Main methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>X</td>
<td>(x)</td>
<td>X</td>
<td>Exoratory, Research Clarification</td>
<td>Systematic literature review</td>
</tr>
<tr>
<td></td>
<td>(x)</td>
<td>X</td>
<td>(x)</td>
<td>Descriptive study</td>
<td>Multiple-case study, in depth literature review</td>
</tr>
<tr>
<td>B</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Exoratory, Prescriptive study</td>
<td>Literature review, Theoretical case study</td>
</tr>
<tr>
<td>C</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Exoratory, Prescriptive study</td>
<td>Theoretical case-study</td>
</tr>
<tr>
<td>D</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Each paper presents a study that contributed to the addressing of the research questions of the thesis. The studies respond to the methodological approach as suggested by the previously described design research methodology, aiming to first establish an overview of the current situation to define the knowledge gap, theories, address the gap, and then to verify, validate and/or suggest improvements. The contribution of each paper to the research questions are shown in Table 3. The following subsections of this chapter, 4.1-4.4, provide summaries and more detailed statements of contribution of each paper.

4.1 Paper A

Integrating Sustainability in Product Requirements

Published as

Summary

In this paper, my colleague and I propose a systematic approach to integrate sustainability considerations in product requirements. The approach consists of two main components, where the first one is a systematic approach to identify which sustainability criteria to consider in a design project, as well as corresponding indicators to enable performance evaluations against these criteria. This systematic process was developed by the co-author in an action research study where company-contextual sustainability criteria, called ‘leading sustainability criteria, are identified using a strategic sustainability perspective. In practice this means that a systemic, principle-based definition of sustainability is coupled with backcasting to derive which sustainability criteria to emphasize in a long-, respectively short-term perspective. In this way no sustainability dimensions or lifecycle phases are excluded from the company’s design for the sustainability strategy. The second component, and my main novel contribution to the paper, was the results of a systematic literature review. This literature review aimed to gather an overview of the academic contributions to integrate sustainability in requirements, based on the experienced lack of implementation of design for sustainability tools and methods. The experience of both industry and academia was that sustainability considerations, if additional to, and/or, in conflict with traditional design performance variables, will not be prioritized unless integrated in the requirement specification. The systematic literature review classified proposed frameworks, methodologies and tools published by academia between 2000 and 2017 based on the sustainability perspective and main methodological base. The results indicated that there was a lack of connection between the strategic, tactical and operational decision levels in the identification of sustainability aspects to integrate and that quality function deployment could be used to integrate different stakeholder perspectives when requirement weights are balanced for integration in a product specification. Coupled with the results of the action research study, this knowledge gap suggests an approach to systematically include sustainability criteria that are derived from a contextual and strategic sustainability perspective.

My role and contribution to this paper, besides planning and executing the systematic literature review, was to lead the creative process from which the novel design approach emerged, as well as the writing. With input, discussions and feedback from the co-author, I was responsible for the main share of planning, structuring and editing of the paper, as well as the presentation of the paper at an international conference.

Contribution to the thesis

The systematic literature review study that shaped the reasoning behind the design approach that is suggested in this paper, contributed strongly to the research clarification stage of this thesis. First, it strengthened previous sustainable product development research findings, by providing an overview of the plethora of tools and methods available for the operational engineering environment to support concept generation and selection. It helped me orient in a new field of terms and constructs, showing how results from sustainability assessment tools and design strategy methods
can be approached both qualitatively and quantitatively to be integrated in traditional design support tools. For instance,

- Life Cycle Assessment (LCA) is a dominating method for identification of (environmental-) sustainability criteria to integrate.
- Quality Function Deployment (QFD) can be used for weighting of requirements and concept selection.
- Voice of the customer (VOC) is an approach to integrate sustainability as a stakeholder in weighting processes.
- Theory of Inventive Solving (TRIZ) can be used for concept generation within given sustainability constraints.

However, one of the key findings in this study was that few, or none, of the suggested methods and tools addressed the importance of the sustainability scope, i.e., which sustainability criteria categories are being assessed to identify the sustainability considerations to integrate. This perceived knowledge gap concerning achieving a linkage between organizational decision levels for sustainability considerations formed the basis for the design of the second study.

4.2 Paper B

Profile model for management of sustainability integration in engineering design requirements

Published as


Summary

While paper A gave an overview and indication of the current knowledge gap in academia, my second study took a closer look into literature on requirements engineering, sustainability maturity and industrial practices of these topics. The purpose of this study was to gain a deeper understanding about how sustainability considerations in engineering product design can be addressed through requirement management processes. Five key elements for successful implementation of sustainable product development from a requirement management perspective are presented, demonstrating how organizational sustainability maturity can be linked to the design and structure of a company’s operational management system.

An in-depth literature review on requirements engineering and sustainability maturity was conducted to refine the reference model created from the study in Paper A, which formed the conceptual framework to which the insights from industry could be compared. To collect empirical data, I designed a multiple-case study, in which a total
of seven companies participated after being selected using stratified purposeful sampling. The amount and role of interviewees at each company depended on how familiar the company contact already was with our research team. In the end, I got the opportunity to interview one to three employees from each company, in total 15 interviews, and I was given access to desktop material from two of the companies. The roles of the interviewees varied and included, but were not limited to, responsibility areas such as project management, product planning, quality and certification, sustainability management, system architecture, ecodesign implementation, and research and development. The interviews were of a semi-structured nature and divided into four sections to achieve a sequential scoping towards the main focus area. The first section therefore included generic questions around the companies’ requirement management processes from which key activities, roles, challenges and opportunities could be identified. The second section specifically addressed sustainability considerations in these processes to find out from which sources, and by which means, sustainability aspects are identified together with challenges and opportunities in managing them as requirements. The third section addressed trade-off management to gain an insight into weighting routines and to find out whether any specific methods or tools were used to support design decisions when trade-offs must be made. The fourth section addressed the scope of sustainability adopted by the company and could be used as a more open discussion in which the interviewees could speak freely about challenging or successful examples from their time at the company.

I used a combination of open and structured thematic coding, in two iterations, to analyze the collected case material. First, from reading the validated interview transcripts with support from memos collected during the interview phase, thematic codes emerged inductively. These formed a coding scheme which was applied to all the interviews and could help distinguish patterns or differences in answers to each interview question. The first iteration of coding resulted in seven case reports, one for each company following the same report structure. Thereafter, a code analysis was conducted which formed the basis for a new code scheme which was employed in a second iteration of coding of the case reports. From this, a research report was written which provided insights in form of patterns regarding capabilities to integrate and address sustainability through requirement management practices. Critical activities and roles, examples of methods and tools utilization and implementation, together with challenges and opportunities, were identified in this way. The case companies thus provided examples of how different sustainability scopes and attitudes and implementation strategies can influence the degree in which sustainability is integrated and addressed in design projects.

By triangulating the findings in literature with the results of the multiple-case study, the conceptual reference model could be refined. Through the resulting five key elements, i.e.; Power of the sustainability policy, Scope of the sustainability policy, Type of sustainability implementation in the product development process, Contextual selection of sustainability criteria, and Sustainability capability of decision board; the paper proposes a profile model of management of sustainability in requirements management which correspond to different levels of organizational
sustainability maturity in product innovation. Product developing companies can use the profile model as guidance towards necessary actions that enhance the organizational sustainability maturity. Motivated by a low uptake rate of sustainability design tools in industry and a lack of traceability of sustainability considerations in the chain of decision making throughout an engineering design project, this study brings attention to organizational capabilities for successful implementation of sustainable product development.

In this paper, I was responsible for the design, execution and analysis of the studies, as well as leading the writing process of the paper. My co-author supported with feedback in all these steps.

Contribution to the thesis

The insights from the multiple-case study motivated a focused literature review to support the creation of a theoretical model for sustainability requirements management. Inspired by both design- and sustainable product development literature, a model is proposed which highlights the need for traceability and contextualization to assign priority to requirements in trade-offs, and through that enhance organizational sustainability maturity. This profile model classifies the profile of a company’s management of sustainability in requirements based on five key elements related to sustainability maturity, from the lens of a strategic sustainability perspective. This model constitutes a refined conceptual reference model on which I could base the continuation of my thesis work. For instance, it

- helped scoping the research context to a more focused group of stakeholders in the design process, namely the gate board,
- confirmed that company-internal sustainability scopes determine which sustainability criteria categories a concept is evaluated against, and thus the scope of sustainability assessment tools,
- showed that prioritizing, weighting and selection of requirements is highly based on qualitative discussions. Engineering design tools can be, and are, used to support these discussions but mainly in companies designing and manufacturing complex systems,
- highlighted that requirements sourced from regulatory- or market needs can be highly sustainability-related but are not managed differently than any other requirements. Achieving traceability in i.e., being linked to stakeholder needs, is essential for sustainability considerations to be prioritized in trade-offs.

Based on these insights, I decided, in the continued thesis work, to focus on methods to improve sustainability awareness and understanding in this specific decision context, i.e., the gate board, where requirements are formulated and weighted.
4.3 Paper C

**Addressing Sustainability in Product Requirements from a Systems Perspective**

*Published as*


**Summary**

In this paper, I explored the relationship between the phases of innovation- and design processes and requirement types. Motivated by the perceived lack of systems thinking in the current approaches in industry and academia to address sustainability in design projects, this study investigated if, and in that case when, in the design process a systems’ thinking methodology would be most suitable to introduce. The study showed that from a sustainability- and design perspective, systems thinking may be useful to introduce in early phases of requirements management, in the very early phases and at the highest system level of a complex product. This is, because the high-level requirements, explained as functions that answer to the stakeholder needs, determine the conditions for all subsystems. Trade-offs that occur between requirements at a lower sub-system level will be weighed against the system requirements, why their relationship to sustainability performance criteria should be in focus. By contextualizing the ‘traditionally identified’ requirements within the scope of socio-ecological constraints, sustainability considerations might be captured early enough to be integrated in requirements, and also weighted fairly against variables that are more well-known by the design decision-makers. The group model building method with causal loop diagramming was suggested as a means for this purpose. A prototype model was developed to illustrate how the modelling technique could be used to map relationships between functional requirements and strategic sustainability criteria indicators. This approach exemplified how tailored sustainability criteria indicators, derived from a principled-based sustainability definition including a lifecycle socio-ecological systems perspective coupled with backcasting, could be introduced in early phases of product development projects.

I designed and performed the literature analysis, and the prototype causal loop diagram modelling exercise which the literature suggested. With support and guidance from my co-author, I also led the writing process of this paper.

**Contribution to the thesis**

The study presented in this paper contributes to the thesis in two ways. Firstly, it provides a deepened description of the challenges in requirements management in relation to sustainability:
A product is composed of multiple layers of systems, which are interconnected. Therefore, late changes in requirements on either a full system, or at a sub-system level can be difficult to achieve and may cause costly effects on other systems.

To catch sustainability performance early points towards the earliest requirement management phases, i.e., the phase in which stakeholder needs are transformed into functional requirements to be cascaded to subsystem levels in the requirements architecture.

The second contribution is a proposed direction for a future prescriptive study, hence addressing sub-research question 3:

- The two previous points indicates, that in order to understand how sustainability aspects relate to other needs or functions, a qualitative group model building approach can be useful. Such an approach would allow for qualitative reasoning around system properties that have yet not been defined.

4.4 Paper D

Decision Support for Re-designed Medicinal Products – Assessing consequences of customizable product design on the value chain from a sustainability perspective

Published as


Summary

A purely prescriptive study is presented in this paper. Together, my co-author and I designed a methodological approach for concept evaluation and decision support based on platform modelling and value-driven design whilst integrating a strategic sustainability perspective. The methodology was tested in a context of re-design of pharmaceutical products into scenarios of various levels of customization, allowing assessment and evaluation of value chain impacts. The methodological approach emerged through collaboration, inspired by shared course work in modelling, simulation and optimization in engineering product development and a literature gap concerning value modelling of changes in the pharmaceutical value chain from personalized medicines. Previously, value modelling of pharmaceutical products has been limited to economic perspectives, despite the implied benefit of customization from a societal health perspective. Previous environmental assessments of
pharmaceutical products also allude to increased resource efficiency, which theoretically could be improved with a shift towards a pull- rather than push-to-market business model. Furthermore, this study provided a value assessment that covered the full pharmaceutical value chain for customizable medicines. Due to being purely theoretical, the validity of this study could, however, be improved through practical tests and verification of the results.

While my co-author was responsible for the generation of customized design concepts using platform modelling, I contributed with the application of a strategic sustainability assessment method, SLCA2.0 (Villamil et al., 2018). This method was applied to the platform concepts in a theoretical and comparative manner to derive value scenarios, i.e., how customization might impact the sustainability performance throughout the complete pharmaceutical value chain in the ecological-, social- and economic (manufacturer) dimension. In this way, value drivers for each dimension could be identified and used to simulate six resulting value scenarios. These were generated using the concept screening matrix, utilizing a qualitative comparison and utility function, as described in Ulrich & Eppinger (2012). This last step was also executed by my co-author. The two last authors contributed with feedback and expertise in platform- and value modelling, respectively pharmaceutical product design, as well as on the writing process.

Contribution to the thesis

I use the results from this prescriptive study to address sub-research question 4. It indicates that a strategic sustainability perspective can be coupled with value models to generate support models for design decision-making in the concept development phase. This was demonstrated through the theoretical application of a qualitative sustainable product development assessment method, SLCA2.0, from which sustainability drivers and constraints were identified in three sustainability dimensions. These could then be used to

- Identify value drivers for different product characteristics,
- compare levels of customization to degree of sustainability performance,
- and, show that customized medicinal product design can be preferable from a socio-ecological value perspective, compared to the traditional design.

Furthermore, the study emphasized the need of competence in the team conducting first the sustainability assessment, and secondly the comparative value assessment of the value chain impacts. Therefore, this study provides a strengthened rationale for the future research direction suggested in Paper B, i.e., enhancing sustainability understanding in early requirements management.
5 Discussion: Utilizing requirements to support sustainable product development

‘The basic difficulty in requirements definition is not one of seeing the woods instead of the trees. The real need is for a methodology which, in any given circumstance, will enable an analyst to distinguish one from the other’ (Ross and Schuman, 1997)

Since the beginning of this licentiate research project my research questions and aims have naturally changed. Most influential were the two initial studies which helped me to better frame the goal of my research and, consequently, shape the research questions accordingly. In the following chapter I intend to answer the research questions presented in chapter 1. Figure 6 provides an overview to how each paper contributed to each question. I also want to discuss the validity, reliability and utility of the proposed answers through a methodological discussion. Therefore, I aim to scrutinize the scientific- and industrial contributions of this thesis, as well as propose a direction for my continued research and that of others.

Figure 6. Overview of papers and research questions. Main contributions are shown as ‘X’, while supporting contribution is shown as ‘(X)’.

5.1 Proposed answers to research questions

How can sustainability be integrated in requirements? (RQ1)

What methods are used to integrate sustainability aspects in product requirements? (RQ1.1), How are sustainability criteria and indicators identified? (RQ1.2)

Starting at the beginning, RQ1, in fact composed of two questions, was primarily addressed in Paper A. Being new to the field of design, and even newer to research, this paper helped me to gain an overview over available approaches to sustainability requirements management. This systematic literature review gathered a wide range of
examples of how sustainability considerations can be practically integrated in design support methods and tools. These examples included tools for both concept generation, and concept selection. For example, the application of the Theory of Inventive Solving (TRIZ) or Algorithm of Inventive Solving (ARIZ) can support concept generation with complex design constraints (Kobayashi, 2006; Rathod et al., 2011); Fuzzy Logic can be used to handle the uncertainty of variables (Bereketli and Erol Genevois, 2013) and Multicriteria Decision Making tools, such as Quality Function Deployment (QFD), can be used to support ranking between design concepts or requirements (Vinodh et al., 2014; Romli et al., 2016; Salari et al., 2016). These approaches could be divided into two categories, i.e., as i) separate requirements, or ii) by relating sustainability criteria to traditional design requirements in, e.g., a QFD (Masui et al., 2003; Romli et al., 2015; Popoff and Millet, 2017). The second category was most common, making QFD the most frequently used tool.

The second part of the research question was addressed by investigating the sustainability assessment method applied to identify sustainability criteria and indicators for the QFD integration approaches just mentioned. The most common approach was to use (environmental-) Life Cycle Assessment in various detail levels and with various scopes of impact categories. This step could however also be completely delimited from the study, meaning that the sustainability criteria could be selected ad hoc. Thus, the study indicated a missing link between strategic, tactical and operational decision levels to help designers in selecting which sustainability aspects to integrate. From a strategic sustainability perspective, this lack of traceability induces a risk for sustainability sub-optimizations (Byggeth and Hscohsconer, 2006) as well as lowered probability for prioritizing sustainability in trade-offs, as suggested in previous adjacent research, see e.g. Siva et al., (2018) or Nilsson and Sundin (2018).

Although not being its’ primary objective, Paper B also came to address RQ1. Through its multiple-case study, it provided a glimpse of how industrial practitioners can act in order to more or less purposefully address sustainability through requirements management processes. Examples of different degrees of systematization and implementation of a sustainability policy, through e.g., internal sustainability criteria categories inducing needs for sustainability assessments methods, may guide identification and selection of sustainability-related requirements and associated indicators. This emphasized the need for commitment, i.e., strictness of sustainability policies, to achieve traceability through the organizational decision levels and the connected requirement management process. Weaknesses of currently available sustainable design methods and tools acknowledged in literature, such as a low implementation rate (Held et al., 2018), was furthermore confirmed by this study as no company used tools for the purpose of integrating, or weighting, sustainability into requirements.

What are sustainability requirements and how are they identified and managed in design projects? (RQ2)

RQ2 was also addressed by Paper A and Paper B, however in the opposite order of magnitude compared with RQ1. While paper A showed that a plethora of tools and
methods are available to achieve integration of sustainability criteria in requirement lists once identified, it only discussed the source of these considerations briefly. It concluded that the sustainability criteria to integrate can be sourced from either market standards or regulations, from application of lifecycle assessments or just from expert judgements. What constitutes a sustainability requirement seemed ambiguous, why Paper B was designed specifically around this research question. By addressing the latter part of the research question, the hypothesis that organizational sustainability maturity can be linked to requirement management activities was formed. A high sustainability maturity here means that requirements should be sourced from a strategic socio-ecological systems perspective, why companies were asked to describe their definition of sustainability and their perception of how sustainability is identified.

The objects of the study were to i) identify key elements of requirements management in early product development for sustainability integration, ii) develop a research design and model of requirements management and organizational sustainability maturity in product innovation processes, to be iii) refined from the results of a multiple-case study of industrial examples. By designing and conducting a descriptive study, I aimed to get a deeper understanding of this perceived lack of traceability of sustainability considerations within organizational decision structures. An in-depth literature review of design literature and models for sustainability maturity in product development organizations were coupled with a multiple-case study constituted by semi-structured interviews. The hypothesis derived from concepts, terms and constructs in academic literature could thereby be refined using empirical data which underwent a series of analysis using a combination of open- and structured thematic coding.

The review of sustainability maturity models indicates that high sustainability maturity needs to be supported by requirements management to systematically generate solutions that contribute to a radical sustainability transition (e.g. Ceschin and Gaziliusoy, 2016; Dyllick and Rost, 2018). This requires that a strategic socio-ecological lifecycle systems perspective is adopted and implemented (e.g. Schulte and Hallstedt, 2018). Lower sustainability maturity, i.e., leading to incremental sustainability improvements, e.g. ‘relative’ improvements limited to environmental aspects, or lifecycle phases, can be achieved through a systematized process for identification and selection of sustainability criteria to include in a requirements specification. Even lower maturity may consist of ad hoc requirements from customers, or only following regulations. Five key elements were identified, namely power of the sustainability policy, scope of the sustainability policy, type of sustainability implementation in the product development process, contextual selection of sustainability criteria, and sustainability capability of decision board.

Additional insights that emerged from the open thematic coding were also used to refine the model. These are described in Figure 7 together with the later described five key elements. As the figure indicates, there seems to be a relationship between these factors and the likelihood of including ‘any’ sustainability considerations in requirement specifications, as well as the degree of strategic sustainability perspective applied in the identification of those considerations, and related to that, the organization’s ability to quantify or value the sustainability performance.
In line with previous research results, such as Nilsson, Sundin, and Lindahl (2018), the findings show how traceability and scope of sustainability considerations, and the usefulness of tools and methods for sustainable product development, are linked to the design of organizational processes. In short, my proposed answer to RQ2 is that sustainability requirements are requirements that may be sourced from environmental or social domains but expressed in form of various needs, i.e., market compliance, customer requests, or internal sustainability policies. The source, in turn, affects how the requirements are identified and prioritized in a product development process.

How do you guide concept development and concept selection from a sustainability and value perspective? (RQ3)

- How can sustainability criteria be related to design requirements, using a systems perspective? (RQ3.1)

Paper C mainly contributed to answer RQ3.1. Through a conceptual literature review, which explored terms and constructs within systems- and requirements engineering literature, I attained a better understanding of early requirements management. This was necessary due to two reasons. Firstly, I lacked experience, and thus the understanding of key terms and constructs in the field of engineering design. Secondly, the paper clarified the need of systems thinking in design not only from a sustainability perspective to avoid sustainability sub-optimizations (Byggeth and Hochschorner, 2006), but as general design approach to identify and meet stakeholder needs contextually (Hull et al., 2010). Based on this deepened understanding, a system modelling method for group model building, causal loop diagramming, was tested as it allows structuring of shared mental models in the prevailing decision context (Andersen et al., 2007). A causal loop diagram was modelled aiming to understand whether, and if so which, relationships exist between strategic leading sustainability criteria indicators (Watz and Hallstedt, 2018a) and traditional functional requirements.

By triangulating the literature review findings with empirical findings in two case companies’ operational management systems, a conceptual requirements architecture could be developed. Thereafter, the results of an action research study provided examples of leading sustainability criteria that are identified with a strategic sustainability perspective (Broman and Robért, 2017). In practice, this means that
long-term sustainability criteria first are developed for a strategic organizational level, from which tactical level design guidelines are generated and then operationalized in form of a sustainability compliance index (Hallstedt, 2017). In this way, a systems perspective was applied both to retrieve design requirements and to select contextually relevant sustainability criteria indicators for a theoretical design problem.

As a systems analysis by itself cannot solve a problem, as it is a means for modelling, but instead directs attention to its underlying causes (Coyle, 2000), the conclusions of the literature review and prototype modelling technique application were:

- Application of sustainability systems analysis modelling for product design may be most useful in the domain between stakeholder requirements and the functional requirements level of a product system. More detailed requirements, e.g., design variables, such as physical geometry dimensions of design solutions, are shaped in the embodiment phase where there is little room for changes in the design.
- Simplified causal loop diagrams for the analysis of relationships between requirements and leading sustainability criteria can be created and indicate that both traditional trade-offs and potential sustainability incentives can be modelled.

Research work from Paper C has thereby helped me address RQ3.1 by suggesting that methods for a systems analysis can be applied to qualitatively investigate relationships between design requirements and sustainability criteria. The usefulness of this approach from a strategic sustainability perspective is larger in the earlier phase of the requirement management process, i.e., the systems- and functional domain, rather than in the later solution and embodiment domain. This conclusion is also supported by findings presented in Paper B, where the multiple-case study harvested key characteristics of requirement management processes directly from the industry.

These conclusions formed the basis for the succeeding and final research question of the thesis project by suggesting a focused direction for future studies. Therefore, also Paper D constitutes a minor contributor to answering of RQ3.1. In this paper, it is demonstrated that sustainability performance can be qualitatively assessed in a comparative manner based on physical design characteristics using a strategic sustainability perspective. However, the approach is delimited to the re-design of a product and the validity and reliability of the method as decision support for concept selection is limited to the uncertainty of data regarding how the sustainability assessment results truly affect the value chain. Continued studies should therefore be conducted.

*How do you guide concept development and concept selection from a sustainability and value perspective? (RQ3)*

This final research question of the thesis was mainly addressed by Paper D. My co-author and I designed and conducted a prescriptive case study from which a novel design method emerged. This methodology for the re-design of pharmaceutical
products used platform modelling, sustainability assessment and value modelling to assess the value chain impacts from re-design for customization. From the platform modelling, using the CC-method (Claesson, 2006), a range of product variants with various degrees of customization, and their corresponding engineering characteristics, could be generated. Thereafter value chain impacts were assessed using the qualitative sustainability assessment method SLCA2.0 (Villamil et al., 2018). From this, the value chain impacts throughout the whole lifecycle of the product variant scenarios could be assessed comparatively. Thereafter, value modelling using three sustainability dimensions as stakeholder value drivers were used to assess the concepts.

This study thereby illustrated an approach to integrate a sustainability- and value perspective into concept development, confirming the usability of, and developing a previously proposed approach (Hallstedt et al., 2015). However, the study was only theoretical, and the approach must therefore be tested in practice to be verified and possibly validated. Furthermore, the study did not address how to find correlating value drivers from a business (company-) perspective and socio-ecological perspective. Nevertheless, it indicated that social sustainability performance improvement could be expected from increased customization and that this seemed to correlate with some ecological benefits. Therefore, my proposed answer to this research question is that an integrative and combined methods approach in which a strategic sustainability perspective is integrated can be used to generate alternative value scenarios which can be used in concept development contexts. The interest in sustainability value assessment is highlighted in the comments from case companies regarding opportunities for improved sustainability requirements management in the multiple-case study of Paper B. However, Paper D does not address how this type of methodology should be implemented in the design process. The conclusions of Paper B alludes to the design of requirement management processes as key for sustainability integration tools to be implemented, why this paper indirectly contributed to also this research question.

5.2 Methodological discussion

Having declared a positivist-constructivist research philosophy in the methodology chapter, I found that a comprehensive, study-based qualitative research design framed by the structure of DRM was suitable as a research approach. This was natural, given that both sustainability science and the research field of sustainable design and product development are design-oriented, which requires a thorough understanding and description of the current state to enable changes that lead to the targeted new situation. As case studies are useful for theorizing as well as for theory testing, I decided to use this methodology for the comprehensive descriptive study.

However, writing a thesis based on a collection of articles has been challenging but at the same time an opportunity to practice analysis and synthesis. The process of planning, writing, submitting, reviewing, editing, presenting and publishing conference- and journal papers has forced me to distil the essence of each study to clarify their respective contribution to the main goal and research question. The articles are furthermore all collaboration projects, meaning that I cannot take credit
for all the research work that is presented here. The collaborations have, however, contributed with opportunities to contextualize my studies and provided opportunities to conduct pilot tests of ideas which have emerged through my own research studies. One example is paper A, where the results of my systematic literature review is combined with a strategic approach to identify sustainability aspects for product developing companies (Hallstedt, 2017). Together the results of this combination provide a novel approach to integrate sustainability criteria in a requirement specification. I did not develop this approach alone, and other methods than the ones we suggested could certainly also be combined, but the collaboration suggests a way forward which hopefully can provide guidance to both future research and to the industry. Another example is of course Paper D, in which my main contribution to the study was an application of an already existing Sustainable Product Development method. Together with my co-author, however, we could support each other in contextualizing, making assumptions when needed, and interpreting the results of the combined concept modelling, sustainability assessment and value modelling. As a result, we were able to propose a decision support based on a sequence of design methods.

To assess and evaluate the quality of the research work I have used Crosswell (2014)’s eight validity strategies for qualitative research.

Table 4. Validity strategies applied in this thesis.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Description</th>
<th>Used in paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triangulation</td>
<td>Coherency of themes that emerge from a variety of sources motivates the trustworthiness of findings</td>
<td>All</td>
</tr>
<tr>
<td>Member-checking</td>
<td>Participants can be asked to comment on the accuracy of findings</td>
<td>Paper B</td>
</tr>
<tr>
<td>Rich description of finding</td>
<td>Inviting the readers to thoroughly understand the research context can make the results more realistic.</td>
<td>Paper A, B &amp; C</td>
</tr>
<tr>
<td>Clarify bias</td>
<td>Sharing reflections around the researchers' background and interests' potential weaknesses can be discussed openly</td>
<td>Paper B &amp; D</td>
</tr>
<tr>
<td>Present negative results or discrepant information</td>
<td>Sharing contradictory evidence also allows results to become realistic</td>
<td>Paper B &amp; D</td>
</tr>
<tr>
<td>Prolong research field time</td>
<td>Long-lasting experience with study participants and context enhances accuracy of findings</td>
<td>Paper A &amp; B</td>
</tr>
<tr>
<td>Peer debriefing</td>
<td>Involving another person that can ask critical questions about the findings provides a quality filter</td>
<td>All</td>
</tr>
<tr>
<td>External audit</td>
<td>Similar to the previous strategy but with even less risk for bias</td>
<td>All</td>
</tr>
</tbody>
</table>
Table 4 summarizes the validity strategies applied in each paper. Only one of the papers, Paper B, utilized all strategies. For instance, the paper represents the thorough descriptive study which was the main focus of the thesis project. It contains a rigorous example of triangulation, both in terms of variety of data collection methods, i.e., reviews of academic literature, and as empirical data in form of semi-structured interviews and case documentation. The literature reviews triangulated findings from the academic fields of design- and design for sustainability, the semi-structure interviews were held with representatives of different roles from a variety of industries, and the documents were collected from both operational management systems and product specifications. Member-checking was applied in the form of validation of interview transcripts by interviewees company representatives' validation of in-case reports, cross-case reports, as well as reviews of first paper drafts by colleagues and external reviewers. A stratified purposeful sampling approach was also adopted, meaning that the case representatives selected interviewees after they had been informed about the goal of the study and provided with the interview questions. Aiming to clarify my bias, the interviewees were provided with the same introduction before the interview started. In this way, the participants were provided with my definition of sustainability, as well as my knowledgeability regarding key terms and constructs in design literature.

The questions related to tools and methods for simulation and optimization in requirements management represent a form of discrepant information, as they generated contradictory results compared to predicted outcomes, i.e., the fact that few tools were used for trade-off management and especially for sustainability considerations. Peer debriefing was used in the design of all data collection- and analysis methods, mostly with my co-author and academic main supervisor but also with other team members and with my industrial supervisor. External audit was employed as early results were presented to a couple of the case companies, which provided fruitful feedback that could improve the finalization of the study. Finally, I find that this paper to some extent also utilized prolonged research time, as additional case companies could be added to the study in a later stage which prolonged the time period in which all companies were engaged in the project by being asked for feedback throughout the analysis phase. This allowed for themes saturation, which is a sign of construct-, interpretive and theoretical validity (Croom, 2009).

The representation of validation strategies in the rest of the papers shows that multiple validation strategies can be used also in shorter and more streamlined studies. For instance, both Paper A & C utilized rich description of findings. Achieving transparency in the reporting of the systematic literature review required a detailed description of the process of identifying the papers, as well as their content. Paper C, on the other hand, is an example of how information from a smaller group can be scrutinized on a deeper detail level to better understand a phenomenon. Paper D is an example of where research background, potential biases and contradictory results are well-explained. Here, we reported assumptions, potential improvements and aimed to clearly define in which context the results, theoretically, could be valid. A more typical example of validity through pro-longed research field time may be found in paper A, in which the study generating leading sustainability criteria was based on my co-
author’s longitudinal data collection during an action research study. Peer debriefing was used in all papers, consisting of co-author feedback but also feedback from, e.g., industrial partners and secondary academic supervisors on the pilot causal loop diagram model in Paper B. External audit from senior researchers in adjacent research groups was retrieved for the proposed decision support in Paper D. This paper also represents a transparent discussion on the results validity, stressing that the cases presented were simulated with a high degree of uncertainty.

5.3 Main contributions and outlook

The thesis serves as a foundation for the continuation of my doctoral research. However, already from this thesis there are several contributions to both academia and to industry.

- **Contributions to academia**

Based on the discussion around the eight strategies for good research quality, I consider the study presented in Paper B as the strongest academic contribution from the thesis. The proposed conceptual framework, i.e., the profile model for management of sustainability in requirements, provides a bridge between the fields' sustainability- and design science by identifying and discussing key terms and constructs within engineering design and sustainable product design. A discussion around the results from a sequence of various studies summoned data collected from a variety of sources. Building on the literature review presented in Paper A, the profile model and discussion highlight a lack of traceability and systems contextualization of sustainability considerations as an unexplored factor behind the low industrial uptake of tools and methods for sustainable design. These factors were based on in-depth literature reviews and case studies refined into the five key elements which correlate to characteristics of sustainability maturity in product innovation processes. The key elements constitute a contribution which is supported by previous and adjacent research, that has suggested that more research should be conducted on organizational sustainability implementation and its dependency on, e.g., project management (Brones et al., 2014) and design of operational management systems (Pigosso et al., 2013; Mendoza et al., 2018). Furthermore, the contribution emphasizes the need for contextual, and strategic, sustainability systems thinking in the scope of the organizational sustainability commitment so that sustainability criteria not only are identified, but also addressed and prioritized in trade-offs, hence addressed in design processes.

Essentially, the profile model stresses operationalization of sustainability policies through, e.g., gate models for project management and product development as a crucial stepping stone for further steps towards organizational sustainability maturity. Enhanced sustainability maturity can be achieved if a larger systems perspective is introduced, operationalized and permeates not only the operational management system but also the business model, the mindset of employees and, importantly from the lens of requirement management, that all this is reflected in the earliest discussions about requirement specifications in any design project. In this way, this thesis
contributes to a more detailed understanding of the interplay between organizational decision-making levels in product developing companies. Extrapolated to the conceptual five-level framework as proposed by the FSSD, the findings may emphasize the importance of the strategic guidance level, to which operational management systems, including requirement management processes, as well as gate models and policies may be classified. The design of these processes are critical to allow operationalization of an organizations’ definition of its place and purpose in the socio-ecological system and its vision of success, as these determine how actions and tools are selected and used in decision-making, hence shaping mental models and design spaces of individual decision-makers and designers.

Besides this main contribution, my thesis also offers several interesting opportunities for future research. These are mainly represented by the two explorative and prescriptive studies that can be found in paper C and D. For instance, Paper C opens an opportunity to design and test group model building in the early phase of requirements management, based on a strategic approach to identify and select sustainability criteria. Paper D shows an approach to how value modelling of sustainability scenarios can be integrated in decision support for concept selection. It is also an example of a new industrial context, i.e., the pharmaceutical industry, in which tools and methods for sustainable design can continue to be tested to verify, and/or improve its applicability.

- Contributions to industry

In this licentiate thesis I have emphasized conceptualization and I have designed the research approach accordingly. Hence, the theoretical contribution has been more in focus rather than an implication for practice. However, several contributions to industry are offered in the thesis, as for instance, the proposed profile model for sustainability integration in requirements management, which can be used as guidance in the design of organizational operations management systems in product developing companies. Its five key elements can be used as checkpoints by organizational- or design method developers and they can also provide a basis for the planning of actions combined with results of, e.g., sustainability maturity assessment results (Waage, 2007; Siva et al., 2019), such as e.g. Schulte & Hallstedt (2018).

Three papers suggest approaches to identify and address socio-ecological criteria to integrate in requirements from a strategic sustainability systems context, which can be adopted if the suggested tools and methods are implemented in the operational management system. For instance, as suggested in Paper A, a strategic sustainability perspective can be used to capture both long-term and short-term sustainability aspects in form of leading sustainability criteria. These criteria could be used as an input to group model building activities, as proposed in Paper C, which in turn can foster organizational ‘soft’ capabilities for sustainable product development (e.g. Siva et al., 2019; Gould, 2018; Brones and de Carvahlo, 2017). The illustrative case study in paper D can be used in pharmaceutical industry product design as a source of inspiration from an adjacent field of research to new methods and tools development for sustainable design in addition to sustainable manufacturing where the focus lies
today. The study can, of course, also be used in traditional engineering design companies as an example of how to connect with a wider socio-ecological context using engineering models, i.e., value modelling.

My future research will in greater detail and depth explore these possibilities for integrating a systems perspective in the early phases of design projects by investigating and evaluating how value can be modelled and used in decision-making. The next phase of my PhD project will generate tangible examples and guidelines for companies that want to enhance their organizational sustainability maturity and by that enable design-decision-making that is informed from a strategic sustainability perspective. This will be achieved through continued studies based on implementation case studies of e.g. key elements suggested in the conceptual framework in Paper B, and continued testing of group model building method using systems analysis combined with value modelling.
Matilda Watz
Utilizing requirements to support sustainable product development

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6 Conclusions

In order to develop responsible forms of use and design, we need to equip users and designers with frameworks and methods to assess, and design the mediating role of technologies in people’s lives and in the ways we organize society’ (Verbeek, 2011)

In the light of the challenges that industry face while attempting to contribute to a sustainable development, this thesis sought to generate a deepened understanding about keys to implement a strategic sustainability perspective in the early phases of the product innovation process, that is, sustainable product development, through the lens of requirements management. The overarching question ‘How can requirements be utilized to support Sustainable Product Development’ guided the formulation of three research questions, which were addressed in studies presented in the four papers appended to this thesis.

This thesis contributes to knowledge by emphasizing on the role of early requirements management in engineering design projects as a bridge between the complexity of the sustainability challenge and the operational design environment, and hence as an enabler that allows for identification of characteristics and necessary actions that can enhance organizational sustainability maturity in the product innovation process. These new understandings have been consolidated into a profile model, which is the main contribution of this thesis to industry. Companies can use this model to characterize their sustainability maturity and as guidance towards which requirements management-related actions to consider for implementation of sustainable product development. Academia can use this thesis as an example of how design- and sustainability science, need to be bridged under the umbrella of sustainable design research to speed up society’s transition to a sustainable development. To do so demands that all organizational processes are incentivized, for which requirements constitute as a critical means. Below two sub sections outlines the main findings, contributions and ideas for future research.

6.1 Main findings and contributions

Paper A suggested an approach to identify sustainability criteria to integrate in requirements, using a strategic sustainability perspective. This approach was developed based on the systematic literature review which results constitute as the foundation of the succeeding studies presented in this thesis. The contribution of Paper A to this thesis was thus to provide an overview of existing methods and tools for sustainability integration in requirements, and to identify the gap in research and practice. It showed that a link between the strategic and tactic management levels, and the operational product innovation process was missing in the currently available methods and tools for sustainability integration in requirements for engineering design projects. The contribution of this thesis is therefore an identified shortage among currently available methods and tools for sustainability integration in requirements, which do not address the importance of context when identifying and selecting sustainability criteria. A strategic sustainability perspective is missing. This answers to
RQ1, i.e., ‘how can requirements be integrated in requirements?’ and its sub-questions RQ1.1 and RQ1.2, i.e., ‘what methods and tools are used to integrate sustainability aspects in requirements?’ respectively ‘how are sustainability criteria and indicators identified?’. An overview of papers and research questions was presented in Figure 6.

Paper B aimed to gain a deeper understanding of this gap by investigating the current state of sustainability considerations in requirement management within a group of seven product developing- and manufacturing companies. The study confirmed previous research which have concluded that tools and methods for sustainable design in general have low implementation rate, and that there is a link between operationalization of sustainability commitments and organizational sustainability maturity. Related to the conclusions of the literature review, five key elements were here proposed to characterize successful management of sustainability in requirements, namely power of the sustainability policy, scope of the sustainability policy, type of sustainability implementation in the product development process, contextual selection of sustainability criteria, and sustainability capability of decision board. Compliance to all five elements would correspond to an enhanced level of organizational sustainability maturity in the product innovation process. These results answer to RQ2, i.e., ‘what are sustainability requirements and how are they identified and managed in design projects?’

Paper C elaborated on early findings in the study which was presented mainly in Paper A and B and explored key terms and constructs from design literature and group model building. The paper proposes system analysis using causal loop diagram as a potential method to enhance the organizational capability for sustainable product development in the early phases of requirements management. A prototype approach is presented to demonstrate an example of such an approach, in terms of phases in the product innovation process as well as what information that would be required for- and generated from the method application. Paper C hence contributed to answering RQ3.1, i.e., ‘how can sustainability criteria be related to design requirements, using a systems perspective?’

The prescriptive case study in Paper D showed how a strategic sustainability perspective can be combined with methods and tools for concept generation and selection, coupled with a value perspective. Through the application of a sustainable product development method, re-designed solution concepts were assessed over their lifecycles using the three sustainability dimensions as stakeholder value preferences. In this way, Paper D showed an approach to how concept selection could be guided from a sustainability and value perspective. Moreover, the paper promisingly showed that methods for sustainable product development are applicable in design projects outside the traditional engineering design industry. In this way, the paper provided answers to RQ3, i.e., ‘how do you guide concept development and concept selection from a sustainability and value perspective?’

All together the thesis, through the findings of the included papers, contribute to the continuous development and refinement of the Framework for Strategic Sustainable Development. By scrutinizing a tool, which requirements management may be
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considered as from a FSSD perspective, the thesis has highlighted the role of the strategic guidance level, i.e., its design, decision-power, selected sustainability scope, and strategy to operationalize a sustainability vision and commitment, as means to achieve implementation of Sustainable Product Development in engineering design organizations.

6.2 Future work

In the thesis I have presented a sequence of research studies in which I have explored, described and proposed improvements to enhance organizational sustainability maturity in the product innovation process through the lens of strategic sustainable development and early requirements management in engineering design projects. I have used a combination of qualitative methods to collect and interpret information from literature and practice. Furthermore, I have tested, suggested and developed sustainable product development methods to increase the state of knowledge about implementation of sustainable product development aiming to improve its uptake in industry.

The reliability, validity and credibility of the findings have been discussed, showing that they could be strengthened through continued studies. For instance, reliability of the conclusions in Paper A and B can be improved using expert feedback, e.g., from a larger scope of practitioners and researchers from adjacent fields. In this way, the developed profile model and its proposed five key elements could be refined. The external validity of the results can be tested through case studies, where the profile model is assessed and from which the results can be used for theory building purposes. Similarly, but for the purpose of enhanced internal validity and credibility, the proposed system analysis method for group model building using causal loop diagrams can be tested and evaluated in the situation as indicated by both Paper B and C, i.e., the decision board, and from this it can be refined. A potential continuation of the approach suggested in Paper D can build on the insights from these suggested studies, where verified sustainable product development implementation is combined with value-driven design. In this situation, a future research direction could involve exploration of value models to represent a strategic sustainability perspective in early decision-making of product innovation processes. Then, the operational engineering environment could connect and integrate a system view of the sustainability challenge in early design decisions.
7 References


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6 Conclusions


Raworth, K. (2012). A safe and just space for humanity: can we live within the doughnut. Oxfam Policy and Practice: Climate Change and Resilience, 8(1), 1-26. ISSN: 2053-0234


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Integrating Sustainability in Product Requirements
Matilda Watz
Utilizing requirements to support sustainable product development

Paper A is published as:

Integrating Sustainability in Product Requirements

Watz, Matilda, and Hallstedt, Sophie I.

Abstract
Trade-offs between sustainability criteria and engineering design variables can lead to sub-optimisations and costly short-term priorities. This study explores how sustainability requirements can be identified and integrated in product requirements to guide strategic and tactical decisions in product development including sustainability perspectives. Literature review and action research resulted in a proposed systematic approach that: define sustainability criteria and indicators; use correlation analysis with QFD; and adds identified specific sustainability requirements to requirement list.

Keywords: sustainability, requirements management, early design phase, product development
Introduction

The sustainability performance of a product is highly dependent on decisions made early in the concept phase of product development (Hallstedt, 2017). In this phase, the basic components of a new design are conceptualised through identification of business opportunities, generation and selection of ideas, and, finally, product and technology development (Koen et al., 2001). Sustainability-related design variables are therefore important to identify and use in the early phases to guide a development towards more sustainable solutions (Byggeth et al., 2007). This research aims to explore and learn from previous research how sustainability requirements have been identified and integrated in the product requirements to guide product development.

Previous research has shown that there is a desire among product development practitioners to integrate sustainability criteria into decision support systems (Knight and Jenkins, 2009; Zetterlund et al., 2016). Sustainability aspects might otherwise be given less priority (Gaziulusoy et al., 2013). However, researchers have also concluded that decision support tools designed for sustainable product (and service) development lacks i) a strategic sustainability perspective (Zetterlund et al., 2016) and ii) support for trade-offs between sustainability criteria and traditional design variables (Byggeth and Hochschorner, 2006). These deficiencies can result in sub-optimisations and short-term priorities in trade-off situations, which can be costly for the company in the long run. Furthermore, there is often a lack of a sustainability perspective that includes both an ecological and social sustainability perspective. These perspectives are sometimes separated, as social sustainability has been harder to define and quantify compared to ecological impacts. However, recent work with guidance on social responsibility by the International Standard Organization (SS-ISO 26000:2010) and UNEP’s suggested guidelines for social life-cycle assessment of products (Benoît and Mazijn, 2009) as well as research, e.g., Missimer et. al. (2015), have taken this a step further.

Purpose and aim

In the light of the perceived gap described above, and as sustainability criteria tend to be traded off in favor for traditional design variables (Bertoni, 2017), this study aims to explore i) how research up until now has approached integration of sustainability criteria in product requirements, and ii) how certain sustainability criteria were selected. The research questions are the following: What methods are being applied to facilitate integration of sustainability aspects into product requirements? How are sustainability criteria and indicators identified? In addition, a process that uses sustainability criteria to guide product requirements is suggested. The continuing of this paper is structured as follows; section two outlines a background and description of strategic sustainable product development, section three presents the methodological approach for this research study, section four outlines the results of the literature review, and in section five an introductory approach to strategically define sustainability aspects to consider in product development. Finally, a concluding discussion is held in section six, in which a novel process to guide integration of sustainability in requirements is presented.
A strategic sustainability perspective in the product development process

A strategic sustainability perspective means here that solutions are developed to fit into, or act as stepping stones to other solutions that will fit into, a future sustainable society defined from overarching sustainability principles (SPs) using a backcasting perspective (Dreborg, 1996). This means that in a sustainable society, nature is not subject to systematically increasing … (SP1) …concentrations of substances from the Earth's crust, (SP2) …concentrations of substances produced by society, (SP3) …degradations by physical means, and, in that society people are not subject to structural obstacles to … (SP4) health, (SP5) influence, (SP6) competence, (SP7) impartiality, and, (SP8) meaning-making. (Broman and Robért, 2017; Missimer et al., 2015). This definition does not directly nor easily integrate into the product innovation process; i.e., the principles from a backcasting perspective do not constitute a tool that can simply be embedded into existing decision systems. In short, backcasting means imagining success in the future and then looking back to today to assess the present situation through the lens of this success definition, and to explore ways to reach that success (Dreborg, 1996; Vergragt and Quist, J., 2011). The challenge is to operationalize the sustainability principles and develop commercialized decision support tools. Therefore, previous research suggests informing other tools or integrate other tools that product developers use with SPs, e.g., Robér et al. (2002); Ny et al. (2006); Byggeth et al. (2007); Waage et al. (2007); Thompson et al. (2012). More recent efforts involve both conceptual frameworks for strategic integration of sustainability into company decision making and the product development process, such as the Method for Integrated Product Development oriented to Sustainability (Fernandes et al., 2017). Examples of recent tactical support methods and tools, are Checklist for Sustainable Product Development (Schögg et al., 2017) and the Sustainability Design Space (Hallstedt, 2017), aiming to provide designers and decision makers with strategic qualitatively obtained actions and indicators to be implemented in the early phases of product development. Although these approaches provide strategic guidance to select relevant sustainability criteria and indicators on strategic and tactical levels, they do not address how the criteria and indicators should be identified and integrated into product requirements on the operational level. In Bertoni (2017), operational decision level support is defined as tools to be used in the design environment for decision making, concept generation and down-selection between concepts, requirements and technologies. Tactical decision level support involves e.g. guidelines, indicators or support processes that are framed from the strategic decision level i.e. the top management business targets and strategies. Meta level refers to decision support that expands over more than one organisational decision level. These are the definitions that are applied in this study.

The importance of product requirements for the product development process

The design process is a process under which a product concept is being realised to a product description, a step prior to manufacturing in the product development process. This process is largely driven by product requirements which define the objectives that a design should fulfil, both in terms of structural- and performance
aspects (Zeng and Gu, 1999). A requirement is a "statement that identifies a product or process operational, functional, or design characteristic or constraint, which is unambiguous, testable or measurable, and necessary for product or process acceptability (by consumers or internal quality assurance guidelines)" (The Institute of Electrical and Electronics Engineers, 2007). The requirement list is a key foundation for success in all projects, as it offers guidance and can be used for monitoring the decisions so that they lead towards the overall target, which is to satisfy stakeholder needs (Hull et al., 2005). Adequate requirements are necessary for guiding designers in developing solutions that perform well throughout the whole lifecycle, in regards to economic, ecological and social aspects (The Institute of Electrical and Electronics Engineers, 2007).

Research approach

The research approach of this paper consists of a combination of a systematic literature review and a prescriptive research study conducted at a case company.

Systematic literature review

A systematic review of previous publications, i.e., following a "transparent, rational and replicable" process (Tranfield et al., 2003), was applied to explore the state of the art of the research field, see Figure 1. The search architecture was obtained from two snowball sampling analyses (SBAs), i.e., a study of "references to references" (Wohlin, 2014), of previous academic publications discussing integration of sustainability into product development and requirements. The first SBA started in Jagheer et al. (2017), leading towards authors such as (Byggeth and Hochschorner, 2006; Bovea and Pérez-Belis, 2012; Inoue et al., 2012; Gaziulusoy, Boyle and McDowall, 2013; Hallstedt, Thompson and Lindahl, 2013; Hallstedt, 2017; Schöggl, Baumgartner and Hofer, 2016; Zetterlund, Hallstedt and Broman, 2016). A research map that visualised the referencing between these articles led towards (Hallstedt et al., 2013), which was chosen as a reference point for a second SBA. The second SBA led to authors such as (Byggeth and Hochschorner, 2006; Kaebernick et al., 2003; Lindahl, 2005; Maxwell and Van der Vorst, 2003; Pujari et al., 2004; Waage, 2007), and others.

From summarising and analysing frequency of keywords used in papers found in the SBAs, it was possible to build a concept map which was used as inspiration for the literature search. Frequently used key words, e.g., "sustainability", "criteria", "integration", "product requirement", etc., including similar words, terms or phrases, were used as operators in the search query. The same query was used to search in title, abstracts and key words in Scopus database and within 'topic' in the Web of Science (WoS) database. The searches were limited to journal papers, book chapters and conference proceedings written in English and published after 1999. A brief title and abstract screening was made for filtering the search results, using 'relevancy for integration of sustainability in product requirements' and 'relevancy for sustainability trade-offs' as criteria for inclusion (papers were considered 'relevant' even though only environmental aspects were considered). To complement the search results, a second, streamlined literature search was conducted in the same databases, although now only searching for titles in the Scopus database, but otherwise with the same limitations. The same filtering criteria were applied to the results in the second search. The first search queries combined keywords with relevant Boolean operators, for example, ("sustainab*" AND ("sustainab* product development" OR (similar term)) AND ("decision-making" OR "design requirement*" "product requirement*" OR (similar term)), while
the streamlined search combined words and terms such as ((product*development* OR sustainable*product*development* OR (similar term)) AND (integrat* OR (similar term))). Remaining contributions were added through a third SBA. A first categorisation of papers was made based on the decision level architecture, namely meta, strategic, tactical and operational, as described above. The papers were thereafter sorted in regard to means to manage sustainability- and integration.

**Figure 1. Schematic overview of the literature review process**

**Action research**

A Sustainability Design Space, i.e. strategically tailored leading sustainability criteria, indicators for those, as well as the method itself together with a sustainability compliance index-scale, was developed for a case company in an action research-based study approach (Hallstedt, 2017). Action research (Avison et al., 1999) here meant an involvement of the researcher at the case company, working closely with the design team during several years to understand and reflect on the challenges relevant for developing a Sustainability Design Space. This included several steps: i) gathering data and information about existing sustainability requirements and guidelines, which were crosschecked by using multiple sources to search for regularities and certainty in the data collection, ii) and iii) were descriptive studies in which key sustainability aspects were identified and a sustainability compliance index was formulated, as support for companies to estimate their sustainability maturity level (Hallstedt, 2017). Altogether about 20 company documents and reports, feedback from five workshops, assessment data and semi-structured interviews with product developers and engineers have been used to support the development of the prescriptive results. The findings were validated with pilot tests iv) and iteratively discussed with a design team, which consisted of an expert group of four engineers, active in the early phases of the technology- and product development process at the company. leading sustainability criteria and indicators have been identified for the case company and are presented in the results. The case company is an engine component manufacturer in the aerospace industry in which the research and development department were interested in increasing the capability to integrate a sustainability perspective in their decision-making system. Since an inability to clarify and understand the sustainability implications compared to performance features of concepts had been identified. Sustainability includes a rich set of features important for a successful introduction of new products and product-service solutions to the market. Therefore, a better understanding of relations between requirements and sustainability aspects and of how these can be included in the product requirement list was of interest to the case company.
Literature review results
This chapter will outline the results of the literature review in regards to: decision level in section 4.1 and, integrated approaches with a sustainability perspective in section 4.2.

Sustainability integration efforts per decision level
The literature review showed that efforts to integrate sustainability into product requirements can be found on all decision levels, with different sustainability perspectives and with support from different tools and methods. In total, 75 papers qualified in the initial filtering of the systematic search results. These papers were distributed into four categories; taxonomies and conceptual frameworks, strategic and meta level efforts, tactical methods and tools and operational efforts, as have been described above. Sixteen of these papers were placed in the category of taxonomies and conceptual frameworks and were found useful for the interpretation of the other search results. They are however not described in more detail in this paper.

Strategic decision level and meta-level
Three of the papers described frameworks or methods for inclusion of sustainability in the product development process. Contributions taking place on this level included: the BECE framework (Mendoza et al., 2017) in which backcasting and eco-design are utilised to achieve alignment with circular economy principles; The Value Ideation process (Geissdoerfer et al., 2016) where design thinking is employed in the early innovation process to define alternative value drivers; and the Systemic double flow scenario method (Gaziulusoy et al., 2013) where product requirements are influenced from linking product development projects to societal structures. Four papers proposed meta-level perspectives, i.e., management of sustainability integration in the product development process (Brones and Monteiro De Carvalho, 2015), including both concept generation (Maxwell and Van der Vorst, 2003; Waage, 2007; Waage et al., 2005) and redesign of a concept (Fargnoli et al., 2014).

Tactical decision level
Sixteen papers presented methods to obtain sustainability indicators, or to select design strategies to be used for decision making. Contributions that suggest approaches to defining sustainability-oriented key performance indicators (KPI) and that suggest when in the product development process they should be applied, include Method for integrated product development oriented to sustainability (Fernandes et al., 2017), Checklist for Sustainable Product Development (Schöggl et al., 2017), Strategic eco-design map of the complex products (Keivanpour and Ait Kadi, 2017) and several others, see Table 1. The characteristic property of these contributions is that they offer support for defining sustainability focus areas and indicators for these, but without articulating how these supportive indicators and focus areas should be integrated in the product development process.
Table 1. Overview of strategic-, meta- and tactical approaches

<table>
<thead>
<tr>
<th>Decision level</th>
<th>Results</th>
<th>Name of method/level</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meta/Strategic</td>
<td>Frameworks for implementation of promotion of sustainability into the product development process</td>
<td>ECLC, framework, Value creation process, Systemic double-flow scenario method</td>
<td>Mendosa et al. (2013); Grinberg and Hulst (2016); Gossiaux et al. (2013)</td>
</tr>
<tr>
<td></td>
<td>Modifications/organisation of product development management</td>
<td>Design Management for Sustainability, Sustainability-oriented adaptations on the product development process, Model for integrating ecological, social, and financial factors into business decision-making Method for Sustainable Product</td>
<td>Fargnoli et al. (2014); Waage (2007); Waage et al. (2005); Maxwell and van der Velden (2003)</td>
</tr>
<tr>
<td>Tactical</td>
<td>Select sustainability oriented approach</td>
<td>Matrix-based tools, e.g., Quality Function Deployment (QFD), Functional Analysis (FA),</td>
<td>Kikaniour and Ail-Kull (2017); Fernandes et al. (2016); Hafbildst et al. (2017); Piggot et al. (2016); Pigott et al. (2005); Khan, Safi and Venkat (2006)</td>
</tr>
<tr>
<td></td>
<td>Select sustainability oriented focus/strategy</td>
<td>Checklist for Sustainable Product Development, Integration of environmental and business aspects toward sustainable product development, Methodology of eco-design for the development of more sustainable electro-electronic equipment</td>
<td>Schlegl et al. (2017)</td>
</tr>
</tbody>
</table>

Operational decision level

The largest category consisted of 34 papers describing operational efforts which integrated, and translated, sustainability indicators into product requirements. In contrast to the tactical approaches, operational efforts propose operational support for sustainability integration. Although most contributions combine several methods to facilitate integration, transformation and prioritisation of sustainability oriented aspects, it was possible to distinguish a main focus, see Table 2. Matrix-based tools, e.g., Quality Function Deployment (QFD), Functional Analysis (FA), Modular Design and Axiomatic Design (AD) tools were proposed in 23 of the 34 papers in this category, and thereby constituted the most frequently used approach. Less frequent approaches involved Preference Set-Based Design and Case-based reasoning, e.g. in Inoue et al. (2012), (Life cycle-) costing (Chan et al., 2014; Grote et al., 2007; Lu et al., 2011), and separate sustainability compliance requirements (Broeren et al., 2016; Heintz et al., 2014; Ma and Okudan Kremer, 2014; Peças et al., 2013). These efforts will not be assessed in more detail due to their low representation within the search results.

Matrix tools are commonly used tools for translating different stakeholder requirements into product requirements to be targeted by designers. They use expertise to correlate the stakeholder requirements with traditional design parameters such as cost, weight, manufacturability and so forth. Modular Design and FA can also be combined with QFD, as found among the 15 QFD-focused papers, e.g., in Alemam and Li (2016) and Devanathan et al. (2010). The common characteristic for these approaches is that they semantically correlate sustainability (or rather environmental) aspects into functional requirements. In QFD, for instance, an eco-design strategy such as ‘reduce material use’ can be translated into the functional requirement of ‘low product weight’ (Alemam and Li, 2016; Romli et al., 2015; Salari and Bhuiyan, 2016). Similarly, AD and FA allow designers to construct design parameters from functional requirements, which can be oriented towards sustainability and evaluated in matrices (Beng and Omar, 2014; Lacasa et al., 2015, 2016; Morrison et al., 2013).
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Table 2. Overview of operational approaches

<table>
<thead>
<tr>
<th>Main integrative approach</th>
<th>Number</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matrix tools: Functional Analysis</td>
<td>3</td>
<td>Lacasa, Santolaya and Biedermann (2016); Lacasa et al. (2015); Chou (2014);</td>
</tr>
<tr>
<td>Modular Analysis</td>
<td>18</td>
<td>Popoff, A and Millet, D (2017); Armas and Iii (2016); Germani et al. (2016); Salari and Bhuiyan (2016); Romil et al. (2015); Vinodh, Kamala and Jayakrishna (2014); Russo, Rizz and Mantelassini (2014); Bereketli and Genevoix (2013); Buyukozkan and Cici (2013); Vinodh and Rathod (2011); Zhang et al. (2011); Rathod, Vinodh and Mody (2011); Deynathan et al. (2010); Sekao (2007); Kobayashi (2006); Kobayashi et al. (2005); Kaebernick, Sara and Sun (2003); Masui (2003);</td>
</tr>
<tr>
<td>Quality Function Deployment;</td>
<td>2</td>
<td>Beng and Omar (2014); Morrison et al. (2013);</td>
</tr>
<tr>
<td>Sustainable-compliance</td>
<td>6</td>
<td>Broersen et al. (2016); Ma and Kremer (2015); Heintz, Belaou and Gerbaut (2014); Poudevill et al. (2013); Np and Chuan (2012); Peces et al. (2013);</td>
</tr>
<tr>
<td>Preference Set-based Design / Case-based reasoning</td>
<td>2</td>
<td>Incue et al. (2012); Tong and Chen (2011);</td>
</tr>
<tr>
<td>Lifecycle costing / cost focus</td>
<td>3</td>
<td>Chang, Wang and Paffoni (2014); Lu et al. (2011); Groe et al. (2007);</td>
</tr>
</tbody>
</table>

Sustainability-oriented adaptations of the QFD process

QFD came out as the most frequently used tool for integration of sustainability aspects in the process of generating product requirements and therefore this section will explore the method and its sustainability adaptions in more detail. QFD is a matrix tool that transforms customer requirements into technical- or product- requirements to be fulfilled by all steps in the product development process (ranging from strategies and planning, to manufacturing and sales) (Sullivan, 1986). The House of Quality (HoQ) is an essential part of the QFD, where different customer requirements, ‘Voices of the Customer’ (VoC), are mapped, classified, weighted and related to relevant engineering metrics (Akao, 1990). QFD is an important design tool as it encourages thorough understanding of customer preferences and priorities and because it “provides a tangible method to manage new product development” (Akao and Mazur, 2003). Several efforts have been made to integrate sustainability-oriented aspects into QFD with the aim to support the development of more sustainable products (Popoff and Miller, 2017). Examples will be described in the section below.

Sustainability perspective

The efforts found in this literature review mainly focus on cost, quality and environmental performance, few include social aspects. As described in Hallstedt (2017), a criterion can be defined as a target of a prioritized aspect or the level of the aspect that we strive for, e.g., “no raw material used” and “no hazardous chemicals used”. An indicator can be defined as a measurement or fact, qualitative or quantitative, that can indicate the state or level of the criterion e.g., “material used in total and per unit of product” and “kilograms of persistent bio-accumulative and toxic chemicals used”. The selection of environmental criteria or sustainability indicators can be managed either with support from assessment tools e.g., LCA or eco-design principles, or through an "ad hoc" approach. Ad hoc here refers to how sustainability requirements and indicators are chosen without support from an assessment that defines sustainability criteria with high relevance for the actual product or solution (Mitchell, 1996). An ad hoc approach can thus involve designer preferences or apply the same criteria as in previous research, without a strategic perspective (Ny et al., 2006). Zhang et al. (1999) made improvements to the Green QFD (GFD) (Cristofari et al., 1996) by incorporating life-cycle costing in the GQFDII. Kaebernick et al. (2003) propose the ECQFD, in which environmental performance is introduced as a new VoC in the QFD, where the results are evaluated with a LCA. Kobayashi (2005) proposes using a simplified LCA endpoint analysis combined with a “willingness to pay analysis”, i.e., considering human health, public assets, biodiversity and primary production capacity, to obtain an environmental impact driver. Another way to
include environmental aspects is to use environmental aspects as VoC’s. For instance, Masui et al. (2003) utilise ad hoc eco-design principles concerning, e.g., material and energy consumption, lifetime, end of life, emissions, maintenance, etc., to comply with environmental requirements from governments, recyclers and traditional customers while noting that LCA can be used to define critical design objectives. A similar approach is used in Vinodh, Kamala and Jayakrishna (2014), and in Salari and Bhuian (2016) where the Life Cycle Design Strategies are used to formulate customer requirements in a Green QFD. Romli et al. (2015) and Alemam and Li (2016) use eco-design strategies to formulate environmental criteria, to which ad hoc social considerations, such as human health and working conditions, are added. Recently, Popoff and Millet (2017) proposed the EcoCSP-QFD in which environmental performance, i.e., climate change, human health, ecosystem quality and resources, and costs are used to conduct the QFD. In contrast to these ad hoc efforts, Sakao (2007) suggests using LCA to define environmental hotspots to be translated into requirements. Table 3 summarises the sustainability approaches used by several authors.

Table 3. Approaches to obtain sustainability criteria and indicators

<table>
<thead>
<tr>
<th>LCA or Eco-design principles</th>
<th>AD hoc (LCA) indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Env. LCA and eco-design</td>
<td>Env. LCA and stakeholder analysis</td>
</tr>
<tr>
<td></td>
<td>Env. LCA, WTP</td>
</tr>
<tr>
<td></td>
<td>Streamlined (env.) LCA</td>
</tr>
<tr>
<td>Climate Change, Ecosystem Quality, Human Health and Resources, costs</td>
<td>Quality, costs and env. indicator</td>
</tr>
<tr>
<td>&quot;Env. VoC&quot;</td>
<td>Env. Social, Economic indicators</td>
</tr>
<tr>
<td>POP and E199 (triple-bottom line indicator)</td>
<td>Eco-design principle indicators</td>
</tr>
<tr>
<td>Romli et al. (2015); Brenkell and Gennos (2013); Bayukokken and Otul (2013); Rathod et al. (2013); Brennathan et al. (2010); Sakao (2007)</td>
<td>Zhang et al. (2011); Kobayashi et al. (2005); Kebernick, Kar and Sun (2003)</td>
</tr>
<tr>
<td>Popoff and Millet (2017)</td>
<td>Vinodh and Rathod (2011)</td>
</tr>
<tr>
<td>Kobayashi (2006); Masui (2003); Vinodh et al. (2014); Alemam and Li (2016); Germani et al. (2016); Salari and Bhuian (2016)</td>
<td></td>
</tr>
</tbody>
</table>

An introductory approach to identify and select sustainability indicators to guide product requirements

Based on results from the action research the needs of the case company were: i) to better understand which product requirements that relate to sustainability; ii) to know what additional sustainability-related requirements need to be included; and, iii) to understand how to include these to the product requirement list. An introductory approach to define and select sustainability indicators to guide product requirement is therefore suggested. From the development of the Design Space, leading sustainability criteria and indicators were identified for the case company. Leading sustainability criteria for each life-cycle phase from the Sustainability Design Space were developed and selected to represent the most important sustainability aspects that can be accomplished within the time-constrained early development situation (Hallstedt and Isaksson, 2017). Indicators to the leading criteria were thereafter identified (Jaghbeer et al., 2017). These steps resulted in 23 criteria, 7 leading criteria and 11 indicators, see Figure 2.

This suggested approach does not give answers to how qualitative, and on which level of accuracy, sustainability data can be transferred into quantitative sustainability data in early design stages. For this, further studies are needed. In addition, a better understanding of the relationship and the influence between sustainability indicators
and design requirements is needed to support the identifying of which sustainability requirements to add to the product requirement list in the early design phase. The main contribution of this work is to offer clear reasoning and a systematic support for how to select sustainability indicators to guide product requirements.

| End of life | End of life activities and design that affect the sustainability impact during the end of life phase.
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>All valuable materials are returned to their value-added state, i.e., for manufacturing and recycling.</td>
<td></td>
</tr>
<tr>
<td>Emissions and waste from end-of-life phase must not contribute to air or water pollution.</td>
<td></td>
</tr>
<tr>
<td>No physical depreciation of material caused by waste types of disposal.</td>
<td></td>
</tr>
<tr>
<td>No organizational practices during disposal of life cycle activities that create structural obstacles for people’s health, influence, competence, importance by and meaning-making.</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2. The case company sustainability criteria, the selected leading criteria (marked) and the sustainability indicators derived from the leading sustainability criteria**

**Concluding discussion**

The aim and purpose of this paper was to present the current state of research regarding how to perform integration of sustainability criteria into product requirements. An explorative systematic literature review and a prescriptive research case study were conducted to answer the research questions.

**How can sustainability criteria be integrated into product requirements, and what methods can be used?**

In line with previous research, the importance of sustainability and how it should be integrated in the organisation is decided at a strategic decision level. Practical guidelines and systems to link the strategic objectives are formalised on a tactical decision level, as a means for communication. Product requirements can be interpreted as the operational means for guidance towards the business objectives (Hull et al., 2005). Whether sustainability is included in the product requirements can however be linked to the sustainability commitment on strategic and tactical levels (Schulte and Hallstedt, 2017). There are furthermore two main approaches to manage integration of sustainability criteria into the product requirements; i) as separate requirements such as complying with certain legislations and regulations, or ii) by
relating sustainability criteria to traditional design requirements, e.g., relating "reduce material usage" to "low product weight" in a QFD (Masui et al., 2003; Popoff and Millet, 2017; Romli et al., 2015). The latter was most common within the literature review results, and QFD came out as the most frequently used tool. The sustainability perspective analysis was therefore limited to these results.

**How are sustainability criteria and indicators identified?**

In general, most of the articles focused on the environmental aspects of sustainability and the process for identifying sustainability criteria can be divided into two main perspectives: i) an environmental life-cycle assessment focus from which important sustainability aspects or eco-design strategies could be derived and integrated, or used to formulate separate sustainability requirements; and ii) an ad-hoc approach where no systematic strategy supported the selection of sustainability criteria. Both perspectives lack a full, strategic sustainability perspective, which indicates a gap between tactical efforts to sustainable product development and a gap of operational tools that support translation of sustainability criteria to product requirements.

**Proposed process to strategically integrate sustainability in product requirements**

In line with previous research, e.g., Bertoni (2017), the literature review concludes that tools on the operational level have most room for improvements. For example, tools for requirements generation lack a full sustainability perspective and have a tendency to lack a strategic process for defining suitable sustainability criteria and indicators to be integrated in the requirement list. The results from the prescriptive research case study showed that it is possible to obtain strategic sustainability criteria and indicators based on a full sustainability perspective. Since it is impossible to predict all future effects of unsustainable development, further research will focus on identifying and verifying sustainability indicators that can help companies to contribute to a sustainable development, and how these indicators can be implemented in the organisational environment.

Several operational matrix approaches, of which QFD was the most frequent tool, show that it can be possible to integrate sustainability criteria through correlation with traditional design requirements. From the results obtained in this study it is therefore proposed that sustainability is integrated in product requirements through a strategic approach that: i) defines sustainability criteria and indicators for those criteria; ii) correlates the sustainability criteria with design variables in a QFD; and, iii) adds to the requirement list the sustainability requirements that cannot be related to traditional design requirements.

**Next steps**

To improve and increase the use of this approach, future research will further investigate how sustainability criteria influence traditional design requirements and what the impact is from a selected design solution and from a sustainability perspective, e.g., via system dynamics modelling (Jagheer et al., 2017), or other techniques. A deeper understanding of these relations, and of the possibility to visualise and communicate these, could further be assessed considering their influence on the sustainability awareness and commitment throughout an organisation. This awareness could have an impact on, e.g., the weighting of requirements and or criteria.
in decision making tools. This is an element that was delimited from this study, and that could add to previous research on how sustainability aspects can be quantified, modelled and integrated into traditional value models for decision making, e.g., Hallstedt et al. (2015), Bertoni (2017) and Jaghbeer et al. (2017). The literature review results also contained a range of different efforts that apply Theory of Inventive Solving (TRIZ) or Algorithm of Inventive Solving (ARIZ) to support concept generation in the complex decision situation (Kobayashi, 2006; Rathod et al., 2011), Fuzzy logic to handle the uncertainty of variables (Bereketli and Erol Genevois, 2013) and Multicriteria Decision Making to support ranking between design concepts or requirements (Vinodh, Kamala and Jayakrishna, 2014; Romli et al., 2016; Salari et al., 2016). Future research should also investigate further how these tools can support integration of a full sustainability perspective into the product development process.

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References


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Utilizing requirements to support sustainable product development


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Profile model for management of sustainability integration in engineering design requirements
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Profile model for management of sustainability integration in engineering design requirements

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Abstract
This research provides insights into how sustainability considerations in engineering product design can be addressed through early stages of requirement management processes. Five key elements for successful implementation of sustainable product development from a requirement management perspective are presented, demonstrating how organisational sustainability maturity can be linked to the design and structure of a company’s operational management system. Through a thematic analysis of fifteen interviews with representatives from seven Swedish product developing-and manufacturing companies, critical activities and roles, examples of methods and tools utilisation and implementation, together with challenges and opportunities were identified. This empirical data was used to develop, test and refine a model in which key characteristics of sustainable product design and engineering design were coupled, resulting in a profile model for management of sustainability in requirements. Product developing companies can use the profile model as guidance towards necessary actions that enhance organisational sustainability maturity. Motivated by a low uptake rate of sustainability design tools in industry, this study brings attention to organisational capabilities for successful implementation of sustainable product development. As a lack of traceability is a potential cause, strategic socio-ecological contextualisation of needs is suggested to improve the chain of decision making in engineering design projects. The guiding research question was ‘What are sustainability requirements and how are they identified and managed in design projects?’ The main contribution is a proposed conceptualised model that aims to support design teams to identify and manage sustainability in requirements for engineering design projects. Future studies will test and validate the model.

Key words: sustainable product development; sustainable design; requirement management; traceability, sustainability maturity

Highlights:
- Profile model for sustainability integration in engineering design requirements is proposed.
- Sustainability maturity of product innovation processes linked to requirements traceability.
- Five key elements of early requirements management and sustainability maturity are presented.
- Challenges and opportunities to sustainability integration in requirements shared.
- Model and case-study guides industry- and research actions towards sustainability maturity.
1 Introduction

Implementation of methods and tools, in combination with skills and competencies for sustainable product design and development, are necessary to achieve a systematic generation of solutions needed for a transition to sustainability (Brones and de Carvalho, 2017). The state of an organisation that have achieved such a situation is here referred to as sustainability maturity (Ceschin and Gaziliusoy, 2016). In this context, sustainable product design and development (SPD), is when ‘a strategic sustainability perspective is integrated and implemented into the early phases of the product innovation process. Including a life cycle thinking’ (Hallstedt et al., 2013). From being significantly open in the early phase known as concept development, design freedom is continuously reduced as requirements are refined to align with a projects’ target objectives. This is why design changes are difficult to make later in a design project rather than earlier (Ullman, 2001), and the background to why most of a products’ lifecycle sustainability impact is determined in this early phase (Poudelet et al., 2012).

Unfortunately, industry fails to implement support for SPD into concept development (Held et al., 2018). The plethora of academic contributions offer a multitude of frameworks, methods, tools, guides and design strategies to support practitioners in the design process (Bovea et al., 2012), as sustainability considerations tend not to be prioritised in trade-off against ‘traditional’ design requirements, such as cost, functionality and robustness (Zetterlund et al., 2016). Some research argues that SPD tools therefore must be improved in terms of applicability, i.e., they need to be easy to use and efficient regarding time and effort (Ahmad and Wong, 2018). Other research alludes to organisational capabilities for SPD as leverage points for companies that seek to improve the sustainability performance of their design solutions (Pigosso et al., 2013). Achieving this situation in a company requires that a commitment to sustainability is anchored at the strategic management level, and that it permeates the subsequent organisational management levels (Hallstedt et al., 2013). Otherwise, it is difficult to justify their inclusion in the design rationale (Poorkiany, 2017).

Requirements can only attain high priority if they are solidly sourced from contextual needs (Kotonya and Sommerville, 1996), i.e., specifying why a solution is needed, how to meet the need, and lastly what the solution should be (Hull et al., 2010). The International Council on Systems Engineering, INCOSE (2015), defines requirements as, ‘A statement that identifies a system, product, or process characteristic or constraint, which is unambiguous, clear, unique, stand-alone (not grouped), and verifiable, and is deemed necessary for stakeholder acceptability’. This means that for sustainability to be systematically and strategically considered in the product innovation process, it is essential that it propagates and permeates decisions on all management levels, from strategic through tactical, to operational. Hence, early requirements management might be a potential key to successful implementation of SPD that truly enhances sustainability maturity. However, few of the currently available tools for SPD, i.e., ‘combined’ or adapted design tools that include sustainability criteria, that are designed for application in the concept development phase (Bertoni et al., 2018), acknowledge the importance of
requirements traceability. Instead they demonstrate how ad hoc sustainability criteria can be merged into commonly used design methods and tools, such as Quality Function Deployment (QFD), Theory of Inventive Solving (TRIZ) and functional matrices, see Watz and Hallstedt (2018a). For sustainability considerations to be included in the design rationale, it seems they must be ‘traceable’ back to a need like any other design requirement (Kirkmann, 1998).

Adjacent and recent research also implies a need for traceability. Zhang and Zwolinsky (2017) suggest systematisation, e.g., combining LCA with strategic environmental objectives to create contextual sustainability considerations and from these select operationalisation activities, thus connect strategic company level to the operational. Brones et al. (2017) found that to foster the soft side of ecodesign, necessary activities are, e.g., educational initiatives and enhanced systematisation of ecodesign practises. With a similar reasoning Mendoza et al. (2017) proposed an approach that combines backcasting from circular economy principles with an ecodesign process to guide selection of SPD strategies and selection of ecodesign tools. Furthermore, two recent survey studies with design project managers conclude that i) environmental considerations rarely are formulated as functional requirements (Sihvonen and Partanen, 2016), and ii) despite having declared sustainability commitment in the business strategy, it is rarely prioritised in decision-making (Silvius et al. 2017). Siva et al. (2018) stressed that ad-hoc sustainability criteria induce a risk for sub-optimisations, while an opposite situation with complete absence of pre-defined sustainability criteria or specialist roles relies on culture and sustainability competencies. Nilsson and Sundin (2018) found that main challenges for setting requirements to improve resource-efficiency in integrated product offerings, or product-service systems (PSS), like inclusion of sustainability aspects in traditional manufacturing product development (Paulson and Sundin, 2019), were stakeholder selection, the priorisation of requirements, and understanding their relationships and origins.

The lack of traceability in sustainability requirements can thus be problematic from a sustainability maturity point of view. Several models for sustainability maturity have been presented during the last five years and have in common that they can categorise a company based on their contribution to a sustainability transition. For instance, Ceschin and Gaziliusoy (2016) argue that the product innovation process itself can generate incremental sustainability improvements, while radical PSS innovations or even socio-technical system innovation may originate from strategic level business models. Dyllick and Rost (2017) call this higher level of maturity ‘True Product Sustainability’ in their three-level model that reaches from incremental ecodesign-improvements of ecological aspects to societal value. Similar reasoning can be found in multiple recent contributions. Gouvinhas et al. (2016) suggest a self-evaluation framework where mature sustainability organisations have a sustainability strategy emerging from top management level, that permeates tactical level decisions through governance models and the operational management system. Hence, routines for requirement selection criteria and preferred design support in the product innovation process are influenced. At the highest level of sustainability maturity, social and
environmental issues constitute as core business objectives. Another example is a model consisting of six steps that is proposed by Ormazabal et al. (2017), where environmental strategies reach from reactive, i.e., compliance-oriented, preventive, i.e., a systematised process is implemented, and proactive, i.e., going beyond regulatory compliance. At the highest level, a ‘leading green company’ inspires other companies when ecodesign is turned into a business model. Prendeville et al. (2017) outline a four-phase ecodesign maturity model, emphasising the ecological sustainability dimension. A strategic sustainability perspective is presented in Schulte and Hallstedt (2018) that suggests a template method for self-assessment of sustainability compliance maturity where at the highest level product requirements align with a fully integrated sustainability perspective in the company vision. Without an organisation mature enough to identify needs from a strategic sustainability context, i.e., a socio-ecological lifecycle systems perspective coupled with back-casting from principle-based definition of sustainability (Broman and Robért, 2017), it is unlikely that these needs will be considered in the requirements definition.

Understanding requirements from a socio-ecological perspective and develop the necessary capabilities to manage such requirements in the daily operations, i.e., linking systems challenges to operational level design decisions, are thus necessary for any business that want to remain on the market as sustainability challenges shifts its conditions, i.e., the design context (Gaziulusoy and Brezet, 2015). Therefore, this paper seeks to describe how early management of requirements can be organised to address sustainability in the product innovation process. The aim and scope are as follows.

1.1 Aim, research questions and objectives
Aiming to contribute to both research and industry, this paper seeks to investigate how requirements management can be utilised as a means for improving SPD capabilities and, by that, enhance organisational sustainability maturity. Using the hypothesis that organisational sustainability maturity is linked to requirement management activities, the objective is to i) identify key elements of requirements management in early product development for sustainability integration, ii) develop a research design and model of requirements management and organisational sustainability maturity in product innovation processes, to be iii) refined from the results of a multiple-case study of industrial examples. The research question guiding the study is ‘What are sustainability requirements and how are they identified and managed in design projects?’. The results were triangulated and proposed as a model.

The remaining of this paper is organised as follows: Section 2 describes the research design, section 3 presents the results from a multiple-case study, section 4 outlines a discussion and proposes a refined model, and conclusions and ideas for future research are found in section 5.
2 Research design

A research approach based on a sequenced combination of qualitative methods and triangulation was used, as the purpose of the study is to contribute to a better understanding of the field using insights from practice (Lewis and Grimes, 1999). Following the general steps of the Design Research Methodology (DRM) (Blessing and Chakrabarti, 2009), a literature review first provided a conceptual frame of reference which informed the design of a multiple-case study. The details of each phase in the research design are described below. Table 1 illustrates the research process by showing in which order the studies were conducted and how the findings were combined to construct the results and conclusions.

Table 1. Phases, methodological approach and main outputs for the selected research design

<table>
<thead>
<tr>
<th>Phase</th>
<th>Methods</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Descriptive literature study</td>
<td>Literature review</td>
<td>Theoretical reference model (key terms and constructs, research gap)</td>
</tr>
<tr>
<td>2. Research design &amp; Method development</td>
<td>Opportunistic/Stratified opportunistic sampling, pilot testing</td>
<td>Case identification and selection, methodological design, interview design</td>
</tr>
<tr>
<td>3. Multiple-case data collection</td>
<td>In-depth interviews, document analysis</td>
<td>Interview transcripts, memos, graphical illustrations</td>
</tr>
<tr>
<td>4. Thematic analysis &amp; Triangulation</td>
<td>Open and structured coding, in-case and cross-case validation, triangulation</td>
<td>Refined model, industrial challenges and opportunities</td>
</tr>
</tbody>
</table>

Observation and analysis of current practice, e.g., case studies, can be useful for theory building (Eisenhardt, K. M., 1989). However, in design research the analysis should be based on a theoretical reference model, a conceptual framework (Blessing and Chakrabarti, 2009) providing valid keys and constructs, including terminology and concepts used in the fields of investigation (Cash, 2018). In this study, the reference model was developed by merging key terms and constructs from general design literature and systems engineering and sustainable design. The purposeful sampling (Palinkas et al., 2015) of this literature was based on a snowball approach (Wohlin, 2014). The resulting framework provided a baseline for the classification and categorisation of themes identified in the multiple-case study. The model development, case selection, data collection and analysis are described in the following subsections.

2.1 Model development

Based on reasoning from the literature on SPD and engineering design, a model that illustrates a relationship between early requirement management characteristics and sustainability maturity is developed. A multiple-case study was undertaken to explore and refine this relationship with practical examples from industry (Eisenhardt, 1989). Aiming for both external and internal validity of the developed model is something that requires a balance between the amount of company cases as well as interviewees
together with the level of detail in the questions included in the inquiry (Maxwell, 2012). By triangulating the findings in literature and industry, key elements are refined, tested, and finally proposed and presented as a model.

The concept development funnel by Ulrich and Eppinger (2012) was used to conceptually illustrate how key activities lay ground for the initial requirement specification, see Figure 1. It shows how a list of requirements with relative weights (priority), starts and ends the concept development phase in product innovation processes. A concept is finally selected and a final requirement specification can be elicited at the end of this phase. By coupling this model with sustainability maturity models that describe different levels of organisational- and product capabilities for SPD, a reference model that illustrate a relationship between key elements of early sustainability requirements management is proposed. The model is refined through insights from the multiple-case study.

Figure 1. The concept of development funnel (Ulrich and Eppinger, 2012) and key activities of early requirements management for concept development and evaluation. The three grey dots represent the prioritised requirements which are fed into the funnel, iterated, refined, and finally used as criteria for concept selection.

2.2 Identification and selection of industrial cases

Generalisable themes, patterns and differences derived from case studies need to be identified from, and between, companies of different sizes and industries (Voss, 2009). A combination of opportunistic- and stratified purposeful sampling was therefore adopted to select case companies, desktop material and interviewees (Palinkas et al., 2015). As the validity of external results, a condition for generalisability, is linked to the comparability of the sampled cases, scoped opportunistic sampling was used to identify and select case companies (Maxwell, 2012). Hence, the companies, or company units, that were contacted and invited to participate in this study share the following characteristics; are based in Sweden, active in global business-to-business environments and they develop and manufacture products. The case companies are, furthermore, different in terms of size, industry and type of product offerings, and they are parts of a supply chain. Figure 2 shows the main phases of the multiple-case study, starting with case identification and selection of companies and case representatives (C1-7), interviewees (I1-15), document analysis material sampling (*),
the deliverables of the thematic analysis, in-case reports (CR1-7), and a final cross-case analysis report.

Figure 2. Overview of the multiple case study. The abbreviations are: CX = Case X, IX = Interviewee X, CRX = Case report X. An asterisk (*) indicates that document analysis material was collected.

A sustainability expert with insight into research and development processes selected, based on estimated suitability, interviewees for the researcher after being introduced to the study’s aim, purpose and interview questions. Consequently, the interviewees represent a variety of managing roles, for e.g., product lines, design projects, verification processes, research and development, ecodesign, or corporate sustainability. Desktop review material was retrieved using the same sampling approach, as interviewees provided material after the interviews. Table 2 gives a brief overview of the variety of cases, characterised by industry, process (product) type, according to definitions of generic product innovation processes described in Ulrich and Eppinger (2012). Global outreach and size are described in an approximate number of markets and employees, a larger number in brackets refers to the total number of employees of the corporation globally. The cases are described as C1 for case 1, C2 for case 2, etc., which are the abbreviations used in the remainder of this paper.

2.3 Data collection methods

The main method to collect information from the case companies was in-depth interviews, following the routines for standardised-open ended (semi-structured) interviews, as the purpose was to access ideas, opinions, and reflections from experts within current practice (Maxwell, 2012). The interview protocol was structured according to the guidance for questionnaires and interviews provided by the DRM (Blessing and Chakrabarti, 2009). Hence, an inquiry of pre-defined interview questions was formulated, providing a preferred but not fixed order that allowed for a free flow of conversation. The interview therefore started with generic questions and gradually approached the specific focus area, aiming for contextual understanding, i.e., information about the companies’ requirements management at large as well as detailed descriptions of how sustainability considerations are treated in this process. Slightly overlapping questions were used to ensure that all topics were covered. All interviewees were asked to describe their roles, background, experience, and to estimate their confidence in their answers. Both physical and telephone interviews were held, from which audio recordings and annotations were made. All were included in the transcription phase.
Table 2. Description of case company characteristics.

<table>
<thead>
<tr>
<th>Case</th>
<th>Industry</th>
<th>Product type</th>
<th>Description</th>
<th>Outreach (markets)</th>
<th>Size (employees)</th>
<th>Interviewee roles</th>
</tr>
</thead>
</table>
| C1   | Heavy Equipment | Platform; Complex systems | Platform-based concept development, product has multiple subsystems developed in parallel | 140               | 13 500            | - Technical project manager  
- Program leader, Service solutions  
- Technical project manager  
- Chief architect |
| C2   | Aerospace | Complex systems; High-risk | Product has multiple subsystems developed in parallel, and product safety is critical. | 15                | 2 000 (17 000 globally) | - Lifecycle management engineer  
- Chief verification engineer  
- Chief engineer |
| C3   | Furniture | Generic | Distinct process phases | 30                | 2 300            | - Sustainability manager  
- Test- and verification manager |
| C4   | Chemicals (Process & Paint) | Process-intensive | Concurrent planning of manufacturing/production process and product development | 80                | 2 500 (50 000 globally) | - Research & development unit manager |
| C5   | Industrial Automation/Power grids | Process-intensive | Concurrent planning of manufacturing/production process and product development | 100               | 4 000 (150 000 globally) | - Chief Corporate scientist  
- Material & technology development manager |
| C6   | Sealing solutions | Platform | Platform-based concept development | 80                | 700              | - Global Product manager |
| C7   | Industrial productivity solutions | Quick-Build | Multiple iterations of detailed design and testing within time/budget limits | 180               | 35 000           | - Product compliance manager |

Table 3 shows the interview questions within their respective categories, i.e., requirements management, challenges and opportunities, modelling, and sustainability, which together targeted different parts of the research question. Category 1, requirements engineering, and category 3, modelling, aimed to capture an overview of the management of requirement propagation in each company. The questions therefore focused on distinguishing key activities, roles, support tools and methods, together with generic challenges and opportunities. This provided an overview of how requirements are identified, verified and validated in design projects. Category 2, challenges and opportunities, and category 4, sustainability, aimed to capture an indication of the sustainability maturity level and to scrutinise how this is reflected in the requirement management. In addition, the interviewees were asked to reflect on challenges and opportunities, both with generic requirement management, and with sustainability considerations per se.
Table 3. Interview questions.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Interview questions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Requirements</strong></td>
<td>How are stakeholder interests broken down into requirements? What are the key processes and roles?</td>
</tr>
<tr>
<td>1.1</td>
<td>What is the input to each level of requirements development? Why? (Can you provide a process map?)</td>
</tr>
<tr>
<td>1.2</td>
<td>How do you validate the choice of requirements?</td>
</tr>
<tr>
<td>1.3</td>
<td>How do you handle conflicting interests?</td>
</tr>
<tr>
<td>1.3.1</td>
<td>Can you give examples of typical functional requirements? (i.e. provide a systems specification)</td>
</tr>
<tr>
<td><strong>Challenges</strong></td>
<td>What challenges occur when defining requirements?</td>
</tr>
<tr>
<td>2.1</td>
<td>Are there typical challenges for sustainability aspects?</td>
</tr>
<tr>
<td>2.2</td>
<td>What are the opportunities with your current methods to integrate sustainability?</td>
</tr>
<tr>
<td><strong>Modelling</strong></td>
<td>How do you model and optimise requirement lists?</td>
</tr>
<tr>
<td>3.1</td>
<td>How do you prioritise requirements, i.e. perform weighting and optimisation?</td>
</tr>
<tr>
<td>3.1.1</td>
<td>How are relationships (and trade-offs) between design variables (functional requirements) identified?</td>
</tr>
<tr>
<td>3.1.2</td>
<td>Do you use any specified approach, such as specific tools, methods or experience?</td>
</tr>
<tr>
<td>3.2</td>
<td>How do you use the awareness of these relationships? E.g. in requirements elicitation, weighting or optimisation</td>
</tr>
<tr>
<td>3.3</td>
<td>Do you conduct causal relationship analysis/simulation between requirements? If yes, how?</td>
</tr>
<tr>
<td><strong>Sustainability</strong></td>
<td>How do you identify and manage sustainability aspects in requirements?</td>
</tr>
<tr>
<td>4.1</td>
<td>What is your understanding of sustainability in the context of sustainable product development?</td>
</tr>
<tr>
<td>4.2</td>
<td>How do you currently work with sustainability in requirements? E.g. regulations, business objectives, values, etc?</td>
</tr>
<tr>
<td>4.3</td>
<td>How are other sustainability criteria transformed into requirements?</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Are you identifying sustainability criteria and indicators within your company, and if so how?</td>
</tr>
</tbody>
</table>

To provide additional contextualisation of interview results a document analysis was conducted (Blessing and Chakrabarti, 2009) which supported the succeeding thematic analysis of the interview transcripts. Documents were reviewed at two companies: at C1, by observations of the operational management system and review of additional documentation, e.g., process descriptions, design guides, and product specifications; and at C2, by operational management system observations from which annotations were taken.

2.4 Thematic analysis

In order to test, refine and improve the reference model that was derived from literature, the collected data was analysed using thematic analysis. In practice, this was a phase that consisted of seven main steps using a combination of open and structured coding. The analysis phase was initiated already during the data collection phase as interview transcripts were created immediately after the interviews, thus continuously confirmed by the interviewees. The first two steps of the iterative coding process resulted in seven company case reports, based on the coding of interview transcripts and case documentation, all following the interview inquiry structure. Memos were
documented and generated inductive themes and patterns which were graphically illustrated in flowcharts. The case reports were distributed back to the case companies for verification from each case representatives. A combination of structured and open, thematic coding was thereafter conducted on the case reports. The most frequently used codes in the first phase inspired a set of refined thematic codes which were used as a baseline for the open coding. Open coding was selected since it is useful for analysis of data where the aim is to identify themes and patterns without the risk of missing out on relevant content, a risk associated with purely structured coding (Maxwell, 2012). Emerging themes were mapped against the interview questions to ensure that enough data had been collected. Hence, both organisational- and substantial categories were used for indexing, charting and finally interpretative mapping (Maxwell, 2012). This approach allowed for an analysis in multiple iterations and emerging results to be discussed continuously within the research team. A computer-assisted qualitative analysis software, Atlas.Ti, supported this analysis phase, generating quotation reports and code frequency statistics.

Figure 3. The thematic analysis process was structured according to seven steps.

The lens provided by the interview questions was used also for the document analysis of desktop material provided by C1 and C2. The resulting multiple-case analysis report underwent deductive framework analysis using the theoretical reference model derived from literature (Blessing and Chakrabarti, 2009). In this way a categorising approach was applied, allowing for conceptualisation based on triangulation of literature and multiple-case study results (Eisenhardt, 1989). Figure 3 outlines the thematic analysis process.

3 Results from multiple case-study

As shown in Figure 2, a total of 15 interviews were held with interviewees from the seven case companies using the inquiry presented in Table 3. The following sections present the themes that were found. Figure 4 shows an example of the flowcharts created for each case report, providing an overview of propagation of sustainability criteria in the early phases of requirements management. The figure outlines a thematic illustration of the process for identifying, selecting and weighting of sustainability criteria in the process of establishing a requirement specification and was created inductively during the coding process.
Figure 4. Example of a schematic illustration of flows and management of sustainability considerations in a requirements management process, which was created for each case report.

3.1 Characteristics of early requirement management

In line with literature, all companies consider the establishment of initial requirement specifications as essential, why it often constitutes an early gate criterion in stage-gate models for engineering product design. A material and technology development manager at C5 emphasised the strategy to, at an early stage, have a ‘rather loose requirement list, which throughout the project is concretised. “A third” into the project the goal is to freeze the requirements’. As the gate model defines what assessment methods to apply and when to verify, and ultimately validate requirements, it is key for tools implementation in all design projects. Another critical activity is to gather a multidisciplinary team which interprets needs and transform these into the target objectives, outlined as requirements in an initial product specification. This team, called a gate board, a decision forum, configuration board, etc., is generally summoned by a product owner, system architect, or similar. These decision-makers constitute the team through which requirements are iterated to be refined and ultimately verified. The product compliance manager at C7 gave an illustrative example for the approach found in all cases, ‘Each new project is assigned a management team and a decision board, called a gate board in the stage gate process. The requirements specification is established internally within the management team, which may constitute of product managers for various product segments. It is refined until the point where you find that the scope is appropriate for the product, after which the gate board forum is used to decide if the project will be continued or not’.

It is mainly the expertise within this team that determine the relative weights, i.e., priority of requirements, even though there might be policy documents available that state the preferred selection criteria. These preferred selection criteria can be quality, delivery, cost and functionality (C1), or technical requirement fulfilment (C6). C7 adds that time-to-market is an important selection criterion. This is reflected in a statement from a chief engineer at C2: ‘Typically this has to do with performance, weight, cost, manufacturing robustness, and requirements compliance’. A more open approach seems to be adopted at C3, where the test and verification engineer explains that market preference is the general selection criteria ‘to at all sell the products on their markets, and secondly what
they need to be best in class on their market’, but that a lot of interpretation must be made by the company. At C5, health, safety and integrity have been the factors which cannot be compromised. ‘Conflicting requirements in this category are very difficult to manage and can lead to that the project is closed down’ states the material and technology manager at C5. In this way, the decision board distinguishes between requirements that are critical, and those that can be compromised. Or, as test- and verification engineer at C3 articulated it, ‘Need to have’ and ‘Nice to have’.

The interviews and documents reveal that tools are mainly used for concept generation and final selection and not to support the creation of the initial product specification. For instance, optimisation tools or analysis tools can be utilised to investigate which concept that performs best against the selection criteria, i.e., the prioritised requirements. Some companies, however, mention that support tools are utilised to investigate early concepts’ requirement profiles and their impact on target objectives. Tools for trade-off detection, weighting and optimisation, e.g., N2 diagrams and A3-reporting, were mentioned by the complex- and advanced systems manufacturers. These companies were also characterised by having a highly controlled gate model, which is well illustrated by statements such as ‘there is a governance model for this, making sure that all company divisions are represented and take part during updates or changes of the gate-process’ says the chief corporate scientist, C5. Interestingly, only one company mentions early trade-off detection as a key activity, although the interviews showed that this activity relies mainly on the competency in the gate board. This means that trade-offs between prioritised requirements are solved by a group of people and not tools or individuals, which is exemplified by the chief corporate scientist at C5; ‘I do not solve it on my own but together with the whole committee’.

3.2 Sustainability in requirements

The interviews revealed that various means, methods and tools are used to identify and integrate sustainability in requirement. Some case companies, i.e., C3, C4, C5 and C7, have operationalised their sustainability commitment by implementing determining environmental- or sustainability policies. This means that the chain of decision-making requires absolute sustainability performance improvement, compared to previous designs in all projects. The general means for implementation are gate model criteria which induce a need to define sustainability requirements in each design project, to enable verification of policy compliance. Consequently, a systematised process for identification of sustainability requirements is developed, preceded by one that establish which sustainability impact-, or criteria-, categories that a new concept should be assessed against. The gate model furthermore determines which method to use for the assessment. In this way a systematic approach and operationalisation of a company’s scope of-, and commitment to, sustainability can be operationalised. C4, for instance, has a policy against introducing new materials with worse environmental impact than what is currently used, and they use internal environmental criteria categories such as ‘Being easier to produce, that they require less energy, more efficient, generating less emissions, having a reduced carbon footprint, contributing to a reduced total eco-footprint’ as stated by the research and development unit manager, C4. C3
represents another approach, where the criteria are derived from the strictest environmental label at the prevailing markets, and hence identifies environmental criteria in each project. The test and verification manager at C3 expresses this in the following way: ‘We put together everything that concerns a certain material in one survey and everything concerning another in another survey. Then we find the toughest requirement.’ Among methods used to identify what sustainability criteria to include in the requirements, mainly Environmental Impact Assessment (EIA) and Lifecycle Assessment (LCA) are mentioned. Generally, a previous product is used as a benchmark. A product compliance manager at C7 exemplifies: ‘Very early in the project, when basically only the type of product has been decided and a business case has been established … / …/ We compare the current to the intended new product, where we might find out that the energy consumption during standby needs to be improved, or that certain materials need to be exchanged’.

C1 and C2 lacked an implemented, systematised process to actively work with sustainability. Here, sustainability criteria originated solely from basic market compliance to environmental-, health-, and safety standards, regulations and legislations. Additional sustainability requirements may occur as specific customer requests. In this situation the prevailing sustainability criteria are managed as any traditional requirements, i.e., they can be prioritised in trade-offs depending on the relative priority indicated by the customer. ‘The core business values form the basis but can easily be traded off against a more profitable alternative’ states a program leader for service solutions at C1, referring to the environmental policy. A technical project manager at the same company explains that previous attempts with environmental assessments, when requested by customers, ‘have not resulted in any standardised process’, and, similarly, a chief engineer at C2 states that ‘there are some specific customer requirements that include sustainability aspects’. However, not having a strict sustainability policy does not prevent an active monitoring of sustainability maturity. For instance, C2 use guiding questions at each gate in the product innovation process for this purpose, although without requiring relative sustainability performance improvement. Providing designers with sustainable design guidelines is another example of a less strict approach to encourage sustainability considerations and is mentioned by all companies. In this way, SPD efforts can be implemented to a small degree but without an assurance of continuous sustainability performance improvement.

3.3 Challenges and opportunities
Reflections on generic- and sustainability-specific challenges and opportunities with their requirement management process were collected from all companies. A common denominator was the ‘understanding customer needs’ for generic RM. The complex system developers, C1 and C2, which apply systems engineering thinking to the largest extent of the sample, describe how difficult it is to ensure that all needs are correctly interpreted into system requirements and then broken down into functional specifications and then again physical design parameters. The chief verification engineer at C2 elaborately describes this: ‘we have to be more aware of how the requirements affect the performance – and we need to do the breakdown of requirements more and more by ourselves, meaning that we need to understand what the customers need and are asking us for’. C5 and C7
mention that capturing the actual requirements early enough is challenging, as projects sometimes start before the customer requirements have been discussed in detail. The material and technology development manager at C5 exemplifies this: ‘the customer can even have formulated the request wrong. But this cannot be addressed before the procurement already has been won’. Other challenges that were mentioned were organisational maturity, i.e., not being confident in their RM process, to predict changes in the market or general requirement balancing.

Balancing was however the strongest theme among challenges for sustainability considerations in RM, which is clearly stated by C7’s product compliance manager: ‘it is hard to integrate ad hoc sustainability requirements. To succeed we believe it must be included in the general requirements specification, it cannot be separate requirements for environmental aspects. More indirect examples are provided by the chief corporate scientist at C5 who stated that ‘product performance must exceed the traditional option or there must be a business case where the customer is prepared to pay more for the product’, and C4’s research and development unit manager who describes the challenge as ‘To change the recipes without changing the product properties’. An overview of all challenges and opportunities can be found in Table 4, showing the themes that emerged from the multiple iterations of coding.

Table 4. Challenges and opportunities in requirements management, generic and sustainability specific. The cases have been highlighted for the strongest themes.

<table>
<thead>
<tr>
<th>Generic RM Challenges</th>
<th>Case</th>
<th>Sustainability RM Challenges</th>
<th>Case</th>
<th>Sustainability RM Opportunities</th>
<th>Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organisational maturity</td>
<td>1,2,6</td>
<td>Competence &amp; Ownership</td>
<td>1,2,6</td>
<td>Increase visibility &amp; systematisation</td>
<td>1,2,3,4,5,6,7</td>
</tr>
<tr>
<td>Understanding needs</td>
<td>1,2,3,4,5,6,7</td>
<td>Organisational maturity</td>
<td>2,3,4,5,6,7</td>
<td>Increasing demand</td>
<td>1,3,4,5,7</td>
</tr>
<tr>
<td>Balancing</td>
<td>2,6</td>
<td>Verification</td>
<td>2,3,4,5,6,7</td>
<td>Sustainability value assessment</td>
<td>1,3,4,5,7</td>
</tr>
<tr>
<td>Capturing needs early</td>
<td>3,4,5,7</td>
<td>Balancing</td>
<td>1,2,3,4,5,6,7</td>
<td>Sustainability embedded</td>
<td>1,2,8</td>
</tr>
<tr>
<td>Market change prediction</td>
<td>3,4,5,7</td>
<td>Complexity, Uncertainty, Qualitative</td>
<td>1,3,4,5,7</td>
<td>Culture change</td>
<td>2,6</td>
</tr>
</tbody>
</table>

Almost all case companies mentioned limited organisational maturity, i.e., that sustainability performance improvement possibilities might not even be investigated, due to the scope of the sustainability policy and selected sustainability criteria. This is reflected in a statement by the product compliance manager at C7: ‘measuring is good, but what is most important is to act upon the indicators’, referring to the need to have contextual and not ad hoc sustainability criteria. The chief corporate scientist at C5 shares this view, and states that ‘the questions become quite general to be applicable to all products’. Related to maturity, almost all cases mentioned verification of sustainability requirements, i.e., knowing how the customer values it. A fourth theme was the complexity, uncertainty and qualitative nature of sustainability requirements, i.e., not knowing which data to use and how reliable it is, which is mentioned by all companies but C2 and C6. Only C1, C2 and C6 explicitly mentioned lack of competence and ownership in sustainable design. An illustrative statement came from a technical project manager at C1: ‘To consider other sustainability aspects than those that already pass down
through regulations and traditional requirements management would require company-internal competence, i.e. possibility to demonstrate how requirements that generate a ‘more sustainable solution’ benefit the business’.

Visibility and systematisation were common themes among the mentioned opportunities. A chief architect at C1 states that ‘That is what it comes down to, to visualise, and enable decision-making’, and C3’s sustainability manager emphasises that ‘we need to be clearer in our directives, it might be necessary to define actual requirements instead of guidelines only’, both referring to the need to operationalise their sustainability commitment through requirements propagation. All companies but C2 and C6 perceive growing demand as an opportunity and are investigating how sustainability drives value as an opportunity. For instance, the test and verification engineer at C3 describes how their ‘customers actually set requirements’, while other industries might experience more resistance where the customers settle with just regulatory compliance. Related to this, three companies mentioned that sustainability considerations already exist but are embedded in the requirements, which can be visualised better. Only C2 and C6 mentioned a changing culture, i.e., how the organisation views sustainability, as a specific opportunity. These comments indicate that organisational processes, structures and roles related to sustainability implementation might be a necessary first step towards sustainability maturity but reaching further requires that also soft aspects and skills are developed. A statement from the product compliance manager at C7 summarises this theme in the following way: ‘To succeed we believe it must be included in the general requirements specification’.

4 Discussion: Towards a model of strategic sustainability integration in engineering design from a requirement management perspective

The emphasis on traceability and systems contextualisation as elements for good requirements, together with models for sustainability maturity, influenced the reasoning behind the model development. Reaching from low to high, a lower level would correspond to a regulatory compliance strategy to identify requirements while the highest level of sustainability integration in early requirements management would correspond to high organisational sustainability maturity. Hence, using the concept of development funnel analogy (Ulrich and Eppinger, 2012), sustainability requirements would go from not being identified at all to being included systematically as criteria for both concept generation and the final concept selection. The sustainability scope applied would also increase from incremental ecological improvement towards more radical socio-technical system innovations, e.g., (Dyllick and Rost, 2017). From the open thematic coding of the 15 interviews at the seven companies and the document analysis at two of them, additional insights about early requirements management and sustainability emerged and were also used to refine the model. These are summarised and illustrated in Figure 5. As a result, five key elements of early requirements management are proposed to support organisational sustainability maturity. These key
elements are described in the following paragraphs and thereafter a profile model is proposed in section 4.1, which is used to classify case companies.

![Diagram](image.png)

**Figure 5. Schematic illustration of main findings in triangulated results. Shows key elements for successful implementation of sustainability in requirement management.**

The first element is suggested to be **the power of sustainability policy**. Almost all companies mention that they have environmental policies, sustainability policies, code of conducts, or environment, health and safety policies, and some even offer ecodesign trainings and provide design guidelines. However, not all have committed to these policies in a systematic manner. Consequently, designers are not always incentivised to challenge a concept from any sustainability perspective beyond regulatory compliance, meaning that the viewpoint of sustainability is not considered. Including sustainability aspects in the requirement specification, hence, becomes unlikely. Not all companies have established systematic processes to identify sustainability aspects nor routines for how they should be prioritised. As previously proposed tools for ecodesign and sustainability integration in often assume such a state as a precondition, see e.g. He et al. (2018), Salari and Bhuiyan (2018), Sousa-Zomer and Miguel (2017), or Romli et al. (2015), this could be a potential reason to why ecodesign tools fail to reach implementation. Most companies, i.e., C3, C4, C5, and C7, however, have such policies and have achieved implementation of environmental or sustainability criteria in their gate models. The policies induce strict requirements for all new products to have improved sustainability performance compared to a previous design. This trigger obligatory sustainability assessments in all design projects and corresponds to higher levels of sustainability maturity than when sustainability considerations are limited to regulatory compliance and occasional, ad hoc, customer requests.

The second key element, however, involves **the scope of the sustainability policy**. The sustainability perspective adopted in company policies indicates which sustainability maturity level the organisation aims for, as it declares whether all sustainability dimensions are considered, i.e. the whole socio-ecological system, or if it is limited to, e.g., the ecological dimension. This reasoning is found in several sustainability maturity models. In, for example, Dyllick and Rost (2017) a product at level two, out of a possible three, considers not only incremental improvement of ecological performance aspects but adopts a lifecycle socio-ecological system approach. In this way companies may reduce the risk for sustainability sub-optimisations, i.e., unintended negative impacts in another lifecycle phase or sustainability dimension than the one in focus for an ad-hoc sustainability improvement (Zetterlund and
Hallstedt, 2016). Only one of the companies, Case 5, showed signs of such an approach. Here, safety and integrity are internally defined concept selection criteria that cannot be compromised in trade-offs.

This leads on to a third key element, namely the type of sustainability implementation in the product development process that is, how the sustainability scope is reflected in the implementation of a determining policy. Here, companies with a higher sustainability maturity distinguished themselves through internally defined sustainability criteria categories, i.e., criteria against which all new design concepts are evaluated. This allows for the implementation of SPD tools such as LCA, EIA or guiding questions, as the results of these become a prerequisite for the continuation of the design project. This, combined with the second element discussed above, was furthermore an opportunity for enhanced sustainability considerations, mentioned in the multiple-case study, as it would trigger visualisation of sustainability in the operational management system. The criteria categories that a company decides to use thus reflect which sustainability scope is adopted and thus the capability for SPD.

The fourth element, contextual selection of sustainability criteria to be included in design projects, refers to how a requirement is selected from the assessment in the internal sustainability criteria categories. As traceability and contextual relevance are crucial characteristics of good requirements (Kotonya and Sommerville, 1996), it is proposed that in order to achieve a higher degree of sustainability maturity, the identification of sustainability requirements also needs to adopt a contextual approach. Then, companies could identify and prioritise requirements for products that aim for either incremental improvements, or radical system innovations (Ceschin and Gaziulusoy, 2016) that contribute to sustainability transitions. A strategic sustainability perspective in the identification of internal sustainability criteria categories could possibly support this contextualisation, as it utilises a socio-ecological lifecycle system perspective and a combination of long-term and short-term, i.e., strategic, thinking (Hallstedt, 2017).

The fifth and final key element considers the sustainability capability of the decision board in which the discussion leading to the initial requirement specification takes place. All companies mention the importance of this activity for the requirements management process. Having the right competencies, skills and support for the team which discuss and decide the relative priority of requirements is crucial, as it is the key factor for ensuring that customer needs are interpreted and addressed correctly. Hence, this team can be a leverage point for achieving a shared understanding of sustainability criteria and its relations to the other requirements, which could trigger adequate selection and application of SPD tools (Buchert et al., 2014). The need for this competency is reflected among the challenges mentioned by C1, C2, and C6, all suggesting that there should be a specific stakeholder that ‘owns’ and drives sustainability in the requirement discussions. Another way to approach this could be to provide SPD training to this team as suggested in, e.g., Mendoza et al. (2017).
4.1 Classification of case companies using a profile model for management of sustainability in requirements

The concept development funnel analogy can be used to illustrate implications of a profile model for management of sustainability in requirements on the concept development phase in engineering design. At the ‘Compliance level’, sustainability criteria beyond regulatory compliance are not systematically identified and thus not included in the initial requirement specification. At ‘Compliance+’, additional sustainability criteria beyond regulatory compliance are occasionally identified, but a process for is not yet systematically implemented. Ad hoc sustainability criteria can therefore be a part of the initial requirement specification but not necessarily in the final selection criteria. At the ‘Systematic’ and ‘Ambitious’ levels, sustainability criteria are always included in both initial requirement specification and the final selection criteria. At the ‘Strategic’ level, a contextual approach in which sustainability criteria influence the other design characteristics is fully implemented and thus used both in the initial requirement specification, refinement, and the final concept selection. The profiles are described and illustrated as funnels in Table 5. The type of dots symbolises whether sustainability requirements are systematically identified and included in the requirement specification. At the ‘Strategic’ level, all in- and out-going requirements are influenced by a strategic, socio-ecological lifecycle system perspective.

The key elements of the proposed model can be found in Table 5, where the case companies have been distributed over the profiles. A Compliance profile was assigned to C6, since the interviews revealed a low sustainability maturity and no decision power in the sustainability policy. C1 and C2 showed some indication of ambition to enhance the organisational sustainability maturity, by, for instance, implementing SPD tools. However, the sustainability policies in these organisations do not induce any demand to continuously, nor systematically, improve the sustainability performance of new design solutions. Sustainability requirements are in the first two profiles not sourced, i.e., traceable, unless stated specifically in customer requests (Kirkmann, 1998). They were therefore classified with a Compliance+ profile. Three of the case companies, C3, C4 and C7, did have a determining Sustainability Policy which requires each new design to be better than a previous version. These three companies have also implemented the use of SPD tools, besides guidelines and checklists, such as LCA or EIA to benchmark previous designs to identify in which of the internally defined sustainability criteria categories’ the new product should be improved. The scope of the sustainability policy was, however, limited to the ecological dimension. One case company, C5, was classified with the profile Ambitious, as the internal sustainability criteria categories included some aspect of social considerations alongside the ecological.
Table 5. Profile model for Sustainability in Requirement Management. The model indicates i) the likelihood for a sustainability aspect to be identified, prioritised during weighting and to be included in the final concept selection criteria, and ii) the sustainability perspective from which sustainability criteria are identified.

<table>
<thead>
<tr>
<th>Key elements</th>
<th>Profile</th>
<th>Compliance</th>
<th>Compliance+</th>
<th>Systematic</th>
<th>Ambitious</th>
<th>Strategic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Compliance</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
<td>Forcing</td>
<td>Forcing</td>
<td></td>
</tr>
<tr>
<td>2 Regulatory</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
<td>Forcing</td>
<td>Forcing</td>
<td></td>
</tr>
<tr>
<td>3 Compliance+</td>
<td>Low</td>
<td>Medium</td>
<td>Mainly ecological</td>
<td>Ecological</td>
<td>Mainly ecological attempting to include social</td>
<td></td>
</tr>
<tr>
<td>4 Checklists</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>5 Case company</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
<td></td>
</tr>
</tbody>
</table>

Case company

C6 C1, C2 C3, C4, C7 C5 N/A

Key elements

1) Power of Sustainability Policy; 2) Scope of Sustainability Policy; 3) Type of implementation in product innovation process; 4) Contextual selection of sustainability criteria to include in design projects; 5) Decision board's sustainability capability (knowledge, skills and mandate) to address sustainability from a socio-ecological system perspective

None of the companies demonstrated a contextual selection of sustainability criteria. In practice, this means that the company may settle with an incremental performance improvement in some of the sustainability criteria categories, since the policy then is fulfilled. A risk to miss out on further possibilities or to cause sub-optimisations therefore still prevails. Consequently, none of the case companies were classified with a Strategic profile. The authors suggest that companies that want to achieve this profile could integrate a strategic sustainability perspective, i.e., when a socio-ecological lifecycle system view is adopted and combined with backcasting (Schulte and Hallstedt, 2018), permeate the organisational decision structure. In practice, this would require that such a perspective is integrated in the sustainability policy, the design of the operational management system, selection of sustainability criteria indicators and assessment tools, and influence the decision board discussions. Then, traceable and contextual requirements (Kotonya and Sommerville, 1996) retrieved from a lifecycle system perspective on sustainability could be integrated in the earliest phases of the
requirement management process. The conceptual relationship between the proposed profiles and sustainability maturity is illustrated in Figure 6.

Figure 6. Proposed relationship between organisational sustainability maturity and profile model for management of sustainability in requirements.

5 Conclusions
By alluding to characteristics of good requirements, i.e., traceability and socio-ecological systems contextualisation, this research has contributed to sustainable design research and industry. Design is about satisfying context-dependant needs, and socio-ecological sustainability is a systems’ property which businesses and their stakeholder inherently are dependent on. To understand requirements from a socio-ecological perspective and develop necessary capabilities to manage such requirements in the daily operations is necessary for businesses that want to remain on the market as sustainability challenges shift the design context. Using the hypothesis that the approach to integrate sustainability criteria in the requirements reflects the organisational sustainability maturity level this research aimed to provide insights into how requirement management can be utilised to address sustainability considerations in engineering design projects. Informed by a triangulation of literature from engineering design and SPD, a multiple-case study was designed guided by the research question ‘What are sustainability requirements and how are they identified and managed in design projects?’ which explored key activities and roles, how methods and tools can be organised and used, and which challenges and opportunities companies currently may experience in their current work with sustainability in engineering design. Based on the findings, five key elements were found and proposed as a profile model, consisting of five levels representing characteristics of early requirement management and their relation to organisational sustainability maturity for product innovation. The model can be used to identify which activities to consider for enhancing organisational sustainability maturity of the product innovation process and sustainable product development. The study emphasises that the source for, and process to identify, sustainability criteria affects its priority as a requirement in a product innovation process. The two objectives of the study were achieved through integrating perspectives on requirements and traceability from engineering design literature.
together with models for and sustainability maturity. Together with empirical data from the multiple-case study a model was developed, tested and refined. The model proposes five key elements of sustainability integration in early requirement management and relates to organisational sustainability maturity.

The five key elements that constitute the refined profile model for management of sustainability in requirements are ‘power of sustainability policy’, ‘scope of sustainability’, ‘type of implementation in product innovation process’, ‘contextual selection of sustainability criteria’, and ‘decision board’s sustainability capability’. The profile model proposes the five levels of ‘compliance’, ‘compliance+’, ‘systematic’, ‘ambitious’, and ‘strategic’, corresponding to different levels of sustainability maturity.

Based on the key elements, the seven companies in the multiple-case study were assigned a profile. This showed that having implemented a systematised approach to identify sustainability aspects to integrate in the requirements, together with a strict sustainability policy, can ensure that some, at the minimum incremental, sustainability improvement can be achieved in all design projects. The sustainability competence and the understanding of sustainability’s value in comparison to other design criteria were also pointed out as important, and challenging, factors for sustainability to be prioritised in trade-offs. None of the case companies was assigned the highest profile level, as this would require that a lifecycle socio-ecological systems perspective is fully integrated and implemented throughout the organisational management system and reflected in the selection of requirements for new design solutions, the design rationale.

5.1 Main contributions

This paper contributes to research and practice by highlighting early requirement management as means to increase organisational capabilities for SPD, and thus enhance organisational sustainability maturity of the product innovation process. The main contribution to academia is the introduction of key terms and constructs from engineering design which emphasise system context and traceability as a necessary characteristic of a good requirement. To anchor and integrate a socio-ecological lifecycle system perspective of sustainability throughout the organisational management levels through contextualisation can be the missing key for successful implementation of SPD and, hence, to improve organisational sustainability maturity. This study sheds light on this knowledge gap and suggest an approach to bridge it through the coupling with sustainability maturity models. This research also contributes a profile model that shows the following: Firstly, examples of how commitment to sustainability policies can be achieved through the design of the early requirement management processes; Secondly, how this triggers implementation and selection of SPD tools and methods in, e.g., gate-models for product innovation processes; Thirdly, how certain actions, through the lens of requirements, support enhanced sustainability maturity of the product innovation process. Furthermore, both academia and the industry can take part of the challenges and opportunities from a range of practitioners as inspiration for continued research. For instance, the alignment between literature and practice strongly emphasise a need for improved
The proposed model can aid implementation of sustainable product design and by doing so reduce industrial impacts on the socio-ecological system, in line with principles of a cleaner production. Requirement management, and enhanced sustainability capabilities within it, is key to connect system level sustainability challenges to operational design decisions and should therefore be further explored.

5.2 Research limitations and outlook
The conceptual frame of reference, which articulated the research gap and formed the basis for the design and analysis of the multiple-case study, was well-anchored in key terms and constructs from literature on engineering design as well as literature on sustainable design. Triangulated with results derived from the analysis of the multiple-case study data, the literature findings gave rise to the refined and proposed profile model. Since the case companies together represented a variety of industries offering solutions of different complexity levels, place in the supply chain, and business models, it is assumed that criteria for external validity have been met and that that results can be generalisable within the prevailing context. The context is medium- to large-sized companies within the business-to-business product manufacturing industry, operating under European environmental, and social-, regulations and legislations. The model should be tested further, for instance, sustainability requirements practices of smaller companies could be an area for future studies. This could contribute to the understanding of how organisational size and structure can influence the capabilities for sustainable design decision-making, and to determine which competencies are necessary within the decision board. Aligned with this, the study supports previously suggested future research directions, such as investigating how enhanced sustainability systems thinking capabilities (Watz and Hallstedt, 2018b), and better understanding of sustainability value drivers (Bertoni, 2017) could be used in SPD as means for increased sustainability maturity in product developing companies.

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6 References


Addressing Sustainability in Product Requirements - a Systems Perspective
Matilda Watz
Utilizing requirements to support sustainable product development

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Addressing Sustainability in Product Requirements - a Systems Perspective

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Abstract
Lack of sustainability considerations in product development can lead to unintended consequences that are costly in the long run, and difficult to solve. Furthermore, the sustainability performance of a solution is predominately determined by decisions in the early phases of the design process, in which requirements are formed and which plays an essential role to guide and constrain innovation. The purpose of this paper is therefore to explore possibilities to address previously identified research gaps regarding i) the importance and challenges to integrate sustainability aspects into design requirements, and ii) the need of a strategic approach based on a full socio-ecological sustainability perspective to select which sustainability criteria to integrate. The aim is to investigate how the influence of sustainability aspects on traditional design variables may be modelled using systems thinking, e.g., System Dynamics modelling, as previous research has pointed out this as an area for future research. Against this background this paper explores the potential of a systems thinking perspective within requirements development, and how it can be applied, to favour a strategic sustainability perspective in product development. A conceptual literature review covering systems engineering, requirements engineering and systems dynamics, was conducted to analyse which phase in the requirements development that could benefit from systems thinking to promote a strategic integration of sustainability criteria into the requirement list. The results point towards the domain between stakeholder requirements and functional requirements, to allow building of a shared understanding the full design decision context that can be cascaded through the requirement levels. Furthermore, a systems analysis model can clarify which requirements that are involved in trade-offs and how. In addition, more detailed requirements imply less space for innovation. One outcome of the paper is a simplified causal loop diagram, showing how a systems’ modelling approach can help identify both traditional trade-offs between strategically identified leading sustainability criteria and traditional design requirements. Potential incentives for sustainable design decisions were identified. Future research will focus on improving and testing the suggested approach and investigate how sustainability criteria indicators can be linked to design value drivers.

Keywords: Product Design; Sustainability; Sustainable Product Development; Systems Engineering; Systems Thinking; Causal Loop Diagrams
1 Introduction

The design process is largely driven by product requirements, as these represent the objectives that a design should fulfil, both in terms of technical functionalities and other performance aspects (Zeng and Gu, 1999). Several methods and tools can be used to support the development, refining and selection of different requirement types; choices of method and tool depend on which level of the system that is to be defined. In a design engineering context, different requirement types are applied to separate phases of the design process. For instance, functional requirements define how functions should be formed to satisfy stakeholder requirements, whilst design solutions describe the specific design through which a functional requirement can be satisfied (Hull et al., 2005). During concept generation, a functional architecture can be built to visualise and structure the linkages between these levels of requirements (Raudberget et al., 2015). Within the product development process, decision makers can use several methods and tools to support this work, to gain understanding of the consequences of certain design decisions.

The importance of including sustainability aspects in the requirements have been acknowledged by both industry and academia, and several tools have been proposed to facilitate integration sustainability criteria into product requirement lists. Previously published academic approaches show that modifications of matrix tools such as Quality Function Deployment, or tools that facilitate optimisation in the presence of uncertain variables, such as the Theory of Inventive Solving (TRIZ), the Analytical Hierarchy Process (AHP) or combinations of these, can be employed, see e.g. (Sakao, 2007). Although these tools may be powerful and supportive, recent research findings imply that they lack two things; i) a full socio-ecological sustainability perspective, and ii) a strategic approach to select which sustainability criteria to integrate (Watz & Hallstedt, 2018). This is necessary since sustainability aspects that are not directly demanded by a customer, regulations or legislation, i.e. cannot provide a clear value contribution, otherwise will not be prioritised (Bertoni, 2017). Other research have therefore stressed a need to investigate how traditional design variables are influenced by sustainability aspects using a systems approach, e.g., System Dynamics modelling (Jaghbeer et al., 2017). This direction has also been given attention by recent, adjacent, research in requirements and resource management, highlighting the importance of a thorough understanding of relationships between requirements for improved resource efficiency (Nilsson, 2017).

1.1 Research question and aims

The purpose of this research paper is to build on these previous findings by exploring how a systems perspective can be applied to understand how strategically identified sustainability criteria may be related to traditional design requirements, to avoid the risk of sustainability- and value sub-optimisations in a long-term perspective. These unintended consequences, originates in a lack of awareness and consideration of the full socio-ecological system in the decision context (Bertoni et al., 2017; Cocca and Ganz, 2015). This paper, therefore, aims to explore i) when during the requirements development and elicitation, integration of sustainability aspects can benefit from systems thinking, and ii) test a strategic approach in which sustainability criteria and indicators are selected, and from a systems perspective analyse how these can be
related to traditional design requirements. The research question guiding this study is therefore: How can sustainability criteria be related to traditional design requirements, using a systems perspective?

2 Research approach

To address the aims for this study, a combination of methods was applied. One of the aims was to investigate in which way a systems perspective can be utilised during requirements development, and this was first adduced through a literature review, followed by a small case example. It was decided to conduct a conceptual literature review, which compared to a systematic review is a brief review focused on key publications within the field of interest (Thomas and Hodges, 2010). The results from both steps were used and analysed in a simplified systems analysis model of relationships between requirements and sustainability criteria. In Figure 1, the research approach is illustrated. The figure presents how the methods were applied, and what outcomes they generated.

![Figure 1. Methods used in the study.](image-url)

The purpose of the conceptual literature review was to identify relevant information about methods and tools for requirements elicitation in a Systems Engineering (SE) context, and to investigate within which phase integration of sustainability criteria could benefit from a systems perspective. This was approached by using triangulation of purposefully sampled, peer reviewed academic publications from a database search and by practising snowball analysis (Wohlin, 2014). Key words such as “sustainability” or “ecodesign”, “product design” or product development”, “requirements”, and “systems analysis” or “causal relationships” or “system dynamics”, or similar terms were used in the database search. The Scopus database, was selected for the search as it offers the largest coverage of peer-reviewed academic literature in the fields of science, technology, humanities, social sciences and medicine (Elsevier, 2018). Additionally, the database has proven to provide a satisfactory overview of the sustainable product development field, from the authors’ previous experiences. The literature review data was then combined with material from a case study, in this case analysis of company documentation, e.g., operational management system descriptions and processes. The case study sampled material from both a manufacturer of construction equipment machines and a component manufacturer of aircraft jet engines. From this study, together with literature on systems engineering, it was possible to build a conceptual requirement architecture. From an action research study, leading sustainability criteria and corresponding indicators had been developed (Hallstedt, 2017). In this study, the researcher actively participated in the company’s
technology development team and identified a sustainability design space, based on a strategic sustainability perspective (Broman and Robért, 2017), which included tactical design guidelines, strategic long term criteria and sustainability compliance index.

To investigate how a systems’ thinking perspective can be utilized for the integration of sustainability aspects in requirements development, a causal loop diagram (CLD) for conducting systems analysis was selected as analysis method. CLD helps structuring the entities, and their causal relationships, of a system. It is an analysis method that allows for building and structuring of shared mental models of a problem by modelling it in its context (Andersen et al., 2007). This means that systems analysis cannot be applied with an aim of “solving” a problem, as it is a means for modelling, but it can, instead, direct attention to the underlying processes causing the problem (Coyle, 2000). Here a CLD was developed as an attempt to model relationships between strategic sustainability criteria and traditional design variables.

3 Navigating through the requirements architecture

The conceptual literature review clearly shows that the purposeful activity that design constitutes, is characterised by the goal of delivering solutions that succeed to satisfy stakeholder needs. This can be done through a systematic process for exploring, identifying and refining value opportunities (Lee and Paredis, 2014). The requirement list constitutes tool that both designers and stakeholders use to communicate what it is a design should provide, and to monitor that it does, i.e., fulfils the stated needs (Hull et al., 2005). However, developing solid requirements in early phase product design is a challenge due to the high uncertainty (Ullman, 2003). The design process can therefore be further explained as a process in which requirements are continuously refined and optimised to deliver a solution that provides maximum value, in regard to stakeholder needs and requirements (Collopy and Hollingsworth, 2011).

![Figure 2. The process starts with problem identification on an overall level to solution generation on a detailed level.](image)

There are several theoretical models for the design process, from which organisations use and combine elements to various degrees (Roozenburg and Eekels, 1995). Systems (and requirements-) engineering (SE) and Value Driven Design (VDD), approach the
design process through systematic development, refinement and elicitation of requirements with the aim to help designers reduce complexity without reducing ability to meet stakeholder needs and values. (Isaksson et al., 2013). In SE, requirements can be briefly divided into three levels, namely, stakeholder requirements, system requirements and specific design requirements, Figure 2. Stakeholder requirements state the overall desired needs to be fulfilled, i.e., what the design should achieve, while the system requirements specify how the stakeholder requirements should be met, i.e., which functions and attributes it should provide. The specific design requirements describe the detailed characteristics of the design solution that can provide the desired function, i.e., how the functions should be provided (Hull et al., 2005).

![Figure 2. Example of a requirements architecture, displaying connections between stakeholder requirements and needs, functions, functional requirements (FR) and design solutions (DS).]

### 3.1 Identifying, defining and refining requirements

The early design phases, including innovation, in which conceptual designs are developed and refined, can be called the pre-embodiment phase. Pre-embodiment refers to the fact that there is too little detail in the conceptual design to enable modelling of a so-called detailed physical architecture, i.e., a dimensioned sketch or specified system (Raudberget et al., 2015). This phase facilitates the breakdown of stakeholder requirements into functions and furthermore functional requirements (FR:s), similar to the explanation of system requirements in an SE context. The functions can, however, also be modelled in a functional architecture. Functional requirements, although an exact definition varies depending on context, company, etc., (Eckert, 2013), can thus in general terms be understood as stating what characteristics a design should have in order to fulfill the stakeholder requirements. Below this level, design solutions (DS:s) and related design requirements are specific, again corresponding to the specific design requirements level in an SE context. The DS level allows the design process to step into the embodiment phase where the physical architecture, e.g., dimensioning, form, appearance, etc., is developed (Raudberget et al., 2015). An example of a requirements architecture can be seen in Figure 3.

Functional modelling involves the organising and structuring of FR:s and DS:s, which allows multiple potential design concepts to be visualised in one single diagram. The functional model thus provides designers with an overview of several strategies to solve the stakeholder needs and requirements. However, to understand how the...
different variables in a functional model relate to each other, it is also necessary to
determine which other variables need to be known to define the design, and to avoid
unnecessary trade-offs. Functional analysis methods, such as the Design Structure
Matrix (DSM) provide support in finding coupled variables in a design, i.e., constraints
to the design space (Steward, 1981). Quality Function Deployment (QFD) is another
method that can be used to derive suitable concept solutions and to detect
interdependencies between variables (Akao, 1990). On a more detailed level, Failure
Mode and Effect Analysis (FMEA) (International Electrotechnical Commission,
2006) can be used to obtain an understanding of which design variables are more
critical than others in relation to the desired system function. The utilisation of these
approaches facilitates a structured way to detect trade-offs and to assign weights for
optimisation schemes before detailed specifications, i.e., dimensions, tolerances, etc.,
are defined. Model-based Systems Engineering (MBSE) is an increasingly used
approach that aims to address the same issues by helping designers obtain a holistic
view of the requirements architecture, allowing different design teams understand
how their design decisions may impact other areas of the system design, supporting
optimisation of the requirements against stakeholder requirements (Micouin, 2014).

Optimisation tools are the tools that can be applied to generate design solutions that
consider the trade-offs and coupled variables. The Theory of Inventive Solving
(TRIZ) is an example of a commonly used tool that facilitates concept generation in
an environment of coupled variables that utilises the output from, e.g., a QFD or
functional analysis (ranking of variables) to find an optimal solution (Altshuller, 1997;
Russo et al., 2014). The general shortcoming of optimisation tools, however, is that
they generally lack capacity to optimise in a complex environment with many trade-
offs, why it is necessary to know which ones are critical (Niccolò and Cascini, 2013).
Knowing the relevance of different variables in relation to the stakeholder needs, or
other limiting constraints is, thus, the factor that allows designers to assign adequate
weights in trade-offs, and, then, to perform down-selection between different
conceptual designs (Lee and Paredis, 2014). Figure 4 lists examples of stakeholder
requirements and needs, FR:s and DS:s, based on a combination of results of the
conceptual literature review and case company documentations.

4 Systems thinking for sustainability considerations in early product design

Several sustainability adaptations of the QFD, DSM and FMEA and TRIZ, as described
above, have been proposed to encourage integration of sustainability considerations
in product design (Bovea and Pérez-Belis, 2012; Brones and Monteiro De Carvalho, 2015). Although modelling in general have three main benefits, i.e., promotes awareness building, provides a process for this, and captures new knowledge (Eckert, 2013), the above mentioned approaches do not address the importance of the design teams’ understanding of sustainability’s role in the full design context. This perception affects the input to the following decision making throughout the design process, affecting the detection of trade-offs and the weighting schemes used for optimisation, i.e., the relative importance of sustainability as compared to other requirements (Lee and Paredis, 2014). Furthermore, functional and system innovation has the greatest potential to generate sustainable designs rather than incremental improvements or redesign, commonly referred to as optimisation (Brezet, 1997). The sustainability performance of a design could therefore benefit from a thorough understanding of the sustainability context within the design team and decision makers (Cocca and Ganz, 2015). In that way, the usefulness of functional modelling and optimisation tools could be maximised. Thus, increased awareness about the relationships between design objectives and the (socio-ecological) systems they are interlinked to, is required.

So how can a conceptual understanding be obtained and modelled to form a basis for shared understanding of a problem? Systems analysis can here be a powerful tool as it aims to model the relationships between key entities, e.g., processes, impact factors, etc., within a system, and by that investigate and provide a common understanding of how or why the problem occurs (Repenning and Sterman, 2002). Modelling the feedbacks within a system is crucial to obtain an understanding of its dynamic behaviour. Systems analysis, including CLD and systems dynamics, can thus be employed to help decision makers, and designers, build shared mental models of a system and help avoid sub-optimisations in form of unintended consequences (Morecroft, 2007). Rebound-effects are examples of unintended consequences, such as increased traffic from building larger roads, or increased total energy usage from energy efficiency (Ford, 2010). Quantification of the stocks and flows within the system model makes the model dynamic and allows simulations, enabling analysis of propagated impacts caused by a change in the system over time (Coyle, 2000).

In a CLD, key entities of a problem are assigned links with arrows (showing in which direction the causality goes) and marked with plus or minus depending on the reaction in the influenced entity. Marking the arrow with a plus sign, “+”, indicates that the reaction follows the pattern of the influencing entity, i.e., an increase causes another entity to increase, and accordingly a decrease of the influencing entity causes a decrease at the end node. A minus, “−”, means that the influence leads to an opposite reaction, i.e., an increase in one entity causes decrease in another. The causal relationships within a system can be either balancing (B) or reinforcing (R), where reinforcing relationship behaviour amplifies the growth, or degrowth of entities (Sterman, 2000). See the simplified example in Figure 5. A typical example of reinforcing feedback in a sustainability and product development context is the environmental ripple effects of growth, driven by consumption (Hertwich, 2005). Reinforcing feedbacks are not desirable, since they may cause vicious circles that are difficult to break out of (Lyneis and Sterman, 2016), such as becoming too dependent on a certain resource that at the same time causes negative socio-ecological impacts.
In Laurenti (2016), a CLD displaying the causal relationships between entities of a conventional passenger car system is presented, detecting reinforcing feedbacks between, e.g., economic growth and consumption, and balancing feedbacks related to material recovery. The method could help designers identify additional variables that would not be detected in a conventional LCA, and illustrate mechanisms causing rebound effects. In their work with sustainability due to uninformed decision-making, Lyneis and Sterman (2016) provide another example that shows how companies fall into a “capability trap”, i.e., a costly situation induced by an investment with short-term benefit. Related to sustainable product development, Rodrigues et al. (2017) built a system dynamics model for the business case of Product Service Systems, i.e. designs composed of product- and service combinations (Oliva and Kallenberg, 2003), see Figure 5. The same authors also presented potential indicators to measure the capability of an organisation to implement ecodesign in their product development process (Rodrigues et al., 2016).

5 Discussion - avoiding unintended consequences in sustainable product design

Requirements are necessary drivers and constraints for the design process, and sustainability tends to fail entering requirement lists, or in attaining weight in trade-offs between sustainability performance and traditional design requirements. At the same time, companies are increasingly acknowledging the business risks and benefits with sustainability (Cucuzzella, 2016). One of the challenges organisations face when implementing sustainability considerations in their decision making is to avoid unintended, negative, consequences (Byggeth and Hochschorner, 2006). These unintended consequences can also be referred to as sub-optimisations, “rebound effects”, “side effects”, or similar, and the essence is that if the impacts of a decision are not investigated enough, unintended consequences can occur, and these are in most cases distant in time and place from the actual decision. The occurrence of these effects is generally a consequence of the fact that decision-makers lack a complete picture of the system in which the problem takes place, i.e., the full context (Repenning and Henderson, 2010). In successful practice of sustainable (product-) development, actions should thus be investigated from a full socio-ecological and strategic perspective (Broman and Robért, 2017; Ny, 2009). Similarly, SE and VDD emphasise...
the importance of mapping the problem domain accurately to secure that the right value drivers are identified from which the right requirements can be determined (Isaksson et al., 2013). From this perspective, this paper has exploited requirement level characteristics, as well as commonly used tools and methods that can be used to identify and weight requirements depending on their relative contribution to value maximization to minimise trade-offs. It has also been shown that although several sustainability modifications of these traditional design tools have been proposed in academia, they fail to reach implementation partly due to lack of strategic sustainability perspective (Watz and Hallstedt, 2018).

Against this background, it is argued that utilising systems thinking models in early concept phase have a potential to facilitate integration of sustainability aspects into requirements and to minimise trade-offs between traditional design requirements. The requirement domain, the pre-embodiment phase is characterised by identification and interpretation of stakeholder requirements, and definition of functional requirements (Raudberget et al., 2015). The possibilities for strategic sustainability considerations in requirements development and elicitation may thus benefit from a systems perspective of sustainability in the domain between stakeholder requirements and functional requirements, see Figure 6.

This is supported by that previous research has shown that knowing the relationships between sustainability criteria and requirements is important for improved sustainability considerations in design (Jaghbeer et al., 2017), which should be given attention at all decision levels of an organisation (Pettersen, 2016). As two recent studies imply, understanding these relationships should support avoidance of sub-optimisations from e.g. resource efficiency measures (Nilsson, 2017), or lack of social considerations (Cocca and Ganz, 2015). Adjacent research studies furthermore show the potential of implementing systems thinking in the management systems of product development organisations, to facilitate systematic management of continuous sustainability improvements. Recent examples are Laurenti (2016) and Rodrigues et al. (2016 & 2017), which entails that a lifecycle systems perspective throughout the design process can increase the sustainability awareness, and an organisation’s capacity to improve the sustainability performance of its operations. None of these research studies are however discussing on which decision-, or requirement level that would benefit from a systems perspective.

It is therefore interesting to investigate how a systems analysis method, possibly, can be used to model the relationships within the system of stakeholder requirements, functions and sustainability criteria, the problem domain expressing calling for a solution (Hull et al., 2005). Although other means for systems modelling, such as MBSE, may appear to take a similar approach as systems analysis, they differ in
purpose. Systems analysis focuses on modelling the problem rather than the solution, while MBSE, as well as traditional modelling and optimisation tools, emphasise the solution. CLDs can thus possibly be used to map relationships between traditional design requirements and strategic sustainability criteria and by that improve the understanding of how sustainability performance influences the value of a design. The output, i.e., a shared mental model of how sustainability aspects relate to the product system, could then contribute as an input for traditional functional modelling. A simplified CLD is presented below for this purpose.

5.1 Simplified CLD test model of leading sustainability criteria and design requirements

To conceptually test how to construct a CLD to model the question “how strategic sustainability criteria relate to traditional design variables”, leading sustainability criteria (Hallstedt, 2017) was obtained from Watz & Hallstedt (2018), and assessed in regard to their causal relationships to traditional product requirements obtained from case study companies’ materials. The sustainability criteria include both long- and short-term aspects to consider during the product development process. The criteria and indicators are displayed in Table 1.

Table 1. Leading sustainability criteria and -indicators

<table>
<thead>
<tr>
<th>Lifecycle phase</th>
<th>Leading criteria</th>
<th>Examples of indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw material</td>
<td>Critical material</td>
<td>SCI score (Hallstedt &amp; Isaksson, 2017)</td>
</tr>
<tr>
<td>Production</td>
<td>Recycled materials</td>
<td>% recycled material in product</td>
</tr>
<tr>
<td></td>
<td>Recyclability</td>
<td>% prod. recycling rate</td>
</tr>
<tr>
<td></td>
<td>REACH-listed materials/emissions</td>
<td>Quantity</td>
</tr>
<tr>
<td></td>
<td>Health &amp; safety</td>
<td>Number of injuries</td>
</tr>
<tr>
<td>Distribution</td>
<td>Risk of exposure to hazardous substances</td>
<td>% compared to previous solution</td>
</tr>
<tr>
<td>Use and maintenance</td>
<td>Optimized product/material weight</td>
<td></td>
</tr>
<tr>
<td></td>
<td>No noise to surroundings</td>
<td></td>
</tr>
<tr>
<td>End of life</td>
<td>All valuable materials are returned to</td>
<td>% Re-manufacturable- and</td>
</tr>
<tr>
<td></td>
<td>value chain for remanufacturing and</td>
<td>re-cyclable components</td>
</tr>
<tr>
<td></td>
<td>recycling</td>
<td></td>
</tr>
</tbody>
</table>

Typically, trade-offs between traditional design variables and sustainability performance are explained by the lack of quantitative measures of the sustainability aspects of concern. In a causal loop diagram these are not needed. However, with a short-term perspective more sustainable options may come across as, for example, expensive compared to a less sustainable option (Bertoni, 2017). This typical trade-off is therefore used as an input for a CLD, constructed around the question “how might cost be affected by, or affect, other traditional functional requirements and/or leading sustainability criteria?” The leading sustainability criteria indicators as described in Table 1 were used as sustainability entities, whilst a selection of functional requirements, as presented in Figure 4, were used as entities representing traditional design variables. From these lists a selection of variables was used to form a pilot
CLD. A discussion was held within the research group, determining potential causal relationships between the system entities representing trade-offs or sustainability improvement incentives.

Figure 7. A simplified CLD was developed to test how to visualise trade-off- and opportunity relations between leading sustainability criteria and traditional design requirements.

Figure 7 demonstrates that it was possible to draw a diagram which modelled potential causal relationships between strategically identified sustainability criteria indicators and functional requirements. In the diagram, the traditional functional requirements are represented in normal font style, while leading sustainability indicators are in bold. The diagram displays three potentially reinforcing feedback loops; R1 – recycling and certifying, R2 – material type and recycling, and R3 – safety and cost. Balancing feedback loops can potentially be found in larger loops, i.e., B1 – cost and lifetime, and B2 – safety and cost. Entities that were not causally linked to other entities could still be assigned with their potential impact on other system entities. Product weight may, for instance, affect cost, while failure rate and ease of use and control may impact safety. Typical design trade-offs could be modelled, such as cost and safety (R3), as well as between recyclability and material criticality (R2). The functional requirement of “certifiability” might have a reinforcing relationship to the sustainability criteria of recyclability (R1), which in turn has a positive impact on upgradeability and further cost. The functional requirement of “functionality” was not taken into the diagram since it was directly linked to other design requirements, and in that way not a standalone entity. This could be, and will be, further investigated in a future study where data from several companies can be compiled and modelled together with industry, preferably in accordance with the principles for Group Model Building as described by Sterman (2000).

Concluding remarks and future work
This paper has outlined a conceptual study of how a systems perspective could be utilised to enhance the understanding of how sustainability aspects relate to traditional design variables, and how this understanding can be utilised for developing product requirements. The literature review on modelling, simulation and optimisation in early
phase product development, and requirements engineering, indicated that the domain between stakeholder requirements and functional requirements level of a product system could be a suitable focus for a sustainability systems analysis. Conducting a systems analysis on detailed design variables, such as physical geometry dimensions of a design solution, will reduce the generalisability of the model and the connection to strategic objectives which is necessary to understand the full decision context. In this phase, early product development also starts entering the embodiment phase where there is little room for changes in the design and challenging to achieve more than incremental sustainability improvements. Furthermore, the study showed that constructing a simplified causal loop diagram to analyse relationships between requirements and leading sustainability criteria is possible, indicating that both traditional trade-offs and potential sustainability incentives can be modelled. Future work will focus on gaining more detailed knowledge about how companies currently work with sustainability in product requirements and how systems thinking could benefit their capabilities to perform sustainable product development. The simplified CLD model presented in this paper will be reviewed and enhanced as more data is collected and analysed. Additionally, future research could investigate how sustainability is related to traditional design value drivers.

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**References**


Decision Support for Re-designed Medicinal Products - Assessing consequences of a customizable product design on the value chain from a sustainability perspective
Decision support for re-designed medicinal products - assessing consequences of a customizable product design on the value chain from a sustainability perspective

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Abstract
Despite advances in pharmacological research providing means for individually customized patient attribute treatments, the 'one-size-fits-all' paradigm remains. Customization is associated with cost increases and the value assessment of customized medicinal products shows upon a narrow economic focus. Inspired by value models, emerging in manufacturing industry research, this study suggests a novel methodology encompassing a full sustainability perspective, including the social, economic and ecological dimension, for design decision support for medicinal products. A concept screening matrix is adapted, using sustainability criteria as value indicators. The focus is to create value for the whole pharmaceutical value chain whilst keeping the core purpose of medicinal products, i.e. to bring societal benefits. An illustrative case study presents an application of the methodology on a commercial product for curing hypertension. The traditional product design for hypertension treatment is compared to a customized product design. Results indicate that a customized product design is preferable if value is to be created from a social or ecological sustainability perspective.

Keywords: Personalized medicines, Product architecture, Sustainability, Sustainable product design, Decision making
1 Introduction
Advances in pharmacological research have provided opportunities for individually customized patient attribute treatments. These attributes can be categorized as biological, behavioural and environmental attributes (Crommelin et al., 2011). The current ‘one-size-fits-all’ paradigm in medicine production is challenged. Several attempts have had the ambition of redesigning the medicinal product to improve the customizability. For example, Siiskonen et al. (2018) developed a modularized product concept of oral dosage forms (ODF), more specifically a tablet. These modules provide different functionalities of the product to comply with the patients’ attributes.

However, customization of medicinal products is commonly associated with various cost increases compared to traditional medicinal products due to e.g. new manufacturing technology investments as modularized tablet design requires additional assembly processes to provide an administrable product. Additionally, customization induces an increase in the number of stock-keeping units (SKU), leading to increased complexity in production and distribution - associated with increased cost (Lee et al., 2015). Research regarding cost-efficient customized treatments, such as that of Hatz et al. (2014) and Srai et al. (2015), shows a narrow focus not only being limited to an economic assessment of treatments, overshadowing the core purpose of medicinal products, i.e. treating people, but also a focus on the consequences of a specific phase of the pharmaceutical value chain. More focus is needed on finding medicinal product designs complying with this core purpose and in the end providing value for the whole value chain, for example by conducting a proper cost-benefit analysis.

Research on value-based decision support has emerged in the manufacturing industry, e.g. the aerospace industry, where a full sustainability perspective, i.e. including a social, economic and ecological dimension, has been adopted when assessing new products (Bertoni et al., 2015; Hallstedt et al., 2015). These value models result in a Net Present Value analysis and thus, require translation of criteria into monetary metrics. The concept screening matrix by Ulrich and Eppinger (2012), based on the concept selection method by Pugh (1990), is another value modelling approach where conceptual designs are comparatively related against a reference design, i.e. a translation into costs is not necessary.

To our best knowledge, no studies on product designs and the consequences for the pharmaceutical value chains, from a full sustainability perspective, have been conducted. Thus, inspired by above-mentioned value models, the aim of this research is to address this gap by proposing a novel methodology to support decisions for re-designed medicinal products, more specifically ODF, which is the most common dosage form today (Nagashree, 2015). The ODF is re-designed to embrace a higher level of customization than traditional product designs and the consequences for the value chain are assessed from a full sustainability perspective. The focus is to create value for the pharmaceutical value chain whilst bringing societal benefits. The study adopts the value assessment approach by Ulrich and Eppinger (2012), i.e. concepts are related benefit-wise to a reference concept with respect to chosen criteria. Thus, a concept screening matrix is adapted, allowing the assessment of product concepts using sustainability criteria as value indicators. The research question is ‘How is the value
chain affected from a sustainability perspective due to an introduction of customized product design? An illustrative case study is performed to test the methodology on a commercial product for hypertension treatment. The traditional product design is compared to a customizable product design. The theoretical contribution of this study is a methodology to develop and assess new medicinal product designs, integrating a full sustainability value perspective. The practical contribution is a proposal for how to design a medicinal product to increase product value. The remaining paper is organized as follows: Section 2 outlines the research approach and Section 3 presents the novel methodology. Section 4 describes an illustrative case study to present the application of the methodology. The results from the illustrative case study are presented in Section 5 and discussed in Section 6 jointly with a discussion of the developed methodology. Section 7 concludes the paper and describes future work.

2 Research approach
A sequence of research activities was conducted to address the perceived research gap. First, theory developing studies were conducted to develop a methodology for decision support. These studies included the adoption of a previous study by Sisikonen et al. (2018) to establish a customized product concept (CPC). A qualitative sustainability assessment tool, SLCA2.0 (Villamil et al., 2018), was chosen to estimate sustainability performance of such an early phase design, from a full sustainability perspective. The sustainability performance of the traditional product concept (TPC) was benchmarked in parallel with the aid of established literature and expert knowledge, i.e. researchers in value-driven design and sustainable product development, informed by literature and an expert with detailed knowledge about the industrial case. From literature studies, the value chain of a pharmaceutical product (Aitken, 2016) and the variables prone to be affected due to a change in product design were clarified. Finally, the concept screening matrix by Ulrich and Eppinger (2012) was adapted to enable simulations providing quantitative data on a value comparison of CPC to TPC. Secondly, an illustrative case study was performed to illustrate the application of the developed methodology. A commercial product for curing hypertension was chosen for the illustrative case study.

3 Proposed methodology
To make a value assessment of medicinal products from a sustainability perspective, a methodology is presented in this section. Figure 1 outlines the proposed methodology composed of various parallel and interconnected activities and a description of the activities is provided in the succeeding sections. Section 3.1 describes a sustainability assessment of medicinal products, adaption and execution of the product platform of CPC and describing and qualitatively comparing the TPC and the CPC according to sustainability performance variables (SPVs). Information from the qualitative comparison is used for consequence analysis on the value chain of pharmaceutical products, which is described in Section 3.2. The value chain assessment is quantified into a value model in Section 3.3 to calculate the relative value of the CPC to the TPC.

3.1 Sustainability lifecycle assessment of medicinal products
A sustainability assessment is conducted using SLCA2.0 (Villamil et al., 2018). The sustainability performance of respective product design, the CPC and TPC, is qualitatively assessed from a full sustainability perspective. SLCA2.0 applies backcasting from eight sustainability principles (SPs), corresponding to anthropogenic mechanisms of ecological- (SP 1-3) and social system destruction (SP 4-8), which are described in detail in the Framework for
Strategic Sustainable Development (Broman and Robért, 2017). In this study, a comparative SLCA (Villamil et al., 2018) is conducted, following the general guidelines for a comparative LCA as described in ISO 14001. The two final steps of SLCA2.0 are followed with the aim to qualitatively compare the CPC with the TPC. Templates and guiding questions, summarized in Figure 2, inform each step and this information is complemented by additional literature as well as expert knowledge since this is the first application of the method on a medicinal product. The SPs translate into SPVs and are used to describe the CPC and the TPC. The SPVs originate from the guiding questions shown in Figure 2. The relevant set of questions are chosen by the researchers according to topics found in previous literature conducting sustainability assessments of medicinal products, such as Slater et al. (2007) and Sheldon (2016). Since the literature shows upon a narrow focus on the ecological sustainability dimension, the researchers chose additional questions according to their best judgment. The guiding questions for this study are shown in bold in Figure 2.

**Figure 1. The proposed methodology to support design decisions of medicinal products**

To enable a comparison of the CPC to the TPC, the SPVs need to be transformable into measurable units. SPVs can be of both quantitative, e.g. material consumption and number of SKUs, as well as of qualitative nature, e.g. usage and end-of-life fate.
3.1.1 Product platform development and execution
To describe a CPC according to SPVs, a customized product design is established adopting an approach developed by Siiskonen et al. (2018). Based on the Configurable Component (CC) framework (Claesson, 2006), this platform approach builds on functional modelling to structure the product according to its functional requirements (FR). The FRs are established from a translation of patient attributes to various design parameters. Design solutions (DSs) are provided to FRs, and these are encapsulated as independently functioning configurable components (CC). Constraints (Cs) are used for potential restrictions of functional regions. This model forms the product architecture, i.e. the product platform foundation.

The platform modelling software CCM (Claesson, 2006) is used for modelling and execution of the product platform, generating sets of product variants grounded in the product architecture of CPC. Note that CPC is a concept grounded in one product architecture but due to scalable properties of the CC-objects, sets of product variants can be established. The CCM software is limited to solving a full factorial combinatorial problem and has no inherent function to eliminate unfeasible solutions. Thus, sets of configured product variants are imported into MATLAB to eliminate unfeasible solutions and to quantify the SPVs of the CPC.

3.2 Value chain impact analysis
To assess the overall value created from introducing a CPC, the value chain of a pharmaceutical product is studied with the aim of identifying which phases, the variables of these phases, and how the value of these variables would be affected. The effects are studied by analysing the SLCA2.0 results and complemented by manufacturing performance-related information by Srai et al. (2015) and Harrington et al. (2017). The variables are called value driving impact variables (VDIV) and are categorised according to the sustainability dimension (SD) affected. The value change is stated for each variable.

Figure 3 presents an illustration of the pharmaceutical value chain by Aitken (2016). The value chain is assumed to remain in the current paradigm, but a customized product design is introduced into it. The pharmaceutical value chain consists of three phases, manufacturing of the medicinal product, delivery to dispensing point and dispensing to end user. The manufacturing phase includes activities from research and development to regulatory approval and commercial production (Food and Drug Administration, 2018). Commercial production of medications is divided into primary production, where the raw material for the medication is produced, and into secondary production, the phase during which the final medicinal product is produced. The purpose is to connect product design with manufacturing performance and to succeeding phases i.e. delivery to dispensing point and dispensing to end user and studying the propagation of consequences due to a change in product design. Thus, initial research and regulatory considerations are outside scope. Additionally, the raw material produced, primary production, is assumed to remain static and hence be independent of product design.
3.3 Value modelling

Value modelling is employed for systematic product design decisions. A value function is developed adapting the concept screening matrix by Ulrich and Eppinger (2012). This matrix will provide a quantitative number of the relative value of the CPC compared to TPC. The aim is to find the most value-creating product design. The resulting value function is presented in Equation (1):

\[ U = w_{social} \left( \sum v_{div_{social}} \right) + w_{ecological} \left( \sum v_{div_{ecological}} \right) + w_{eonomic} \left( \sum v_{div_{eonomic}} \right) \]

\( U \) is the relative value of the CPC compared to the TPC. The respective \( w \)'s are weights of each sustainability dimension and are varied to emphasise various preferences. For example, if a product concept performing well from a social sustainability perspective is desired, the weight of this dimension is given a higher quantity. The respective \( v_{div} \)'s describe the value change of VDIVs. The \( v_{div} \)'s for each sustainability dimension are summarized and normalized with respect to the number of VDIVs, \( i,j \) and \( k \), that each dimension embed.

4 Illustrative case study

A commercial medicinal product is used to test the proposed methodology described throughout Section 3. This product is aimed at curing hypertension. Unmanaged hypertension can lead to heart attack and stroke (MacGill, 2018). The product chosen adopts the dosage form of a tablet. The TPC follows the subsequent assumptions; the product design embraces a fully monolithic, i.e. integral product design and embeds a single active pharmaceutical ingredient (API). The function of an API is to provide a therapeutic effect in the body. The API density is \( 1.4 \text{ kg/mm}^3 \). The treatment today is offered in three variants and is described according to API content, 2.5, 5 and 10 mg. These product variants have a flat-faced cylinder shape with a diameter of 8 mm and height of 2.5 mm; hence, the resulting volume of each variant becomes 126 \text{ mm}^3. Additionally, the tablet embeds excipients, lactose and hydroxypropyl methylcellulose (hypromellose), in the 20:80 ratio, and provide the tablet with functions to provide material and modifying the release of API, respectively.

The CPC is assumed to embrace a modularized tablet design consisting of two different types of modules. The function of the first module type is to provide a therapeutic effect and embeds 0.1 mg API. The API is the same as for the TPC. The drug loading of the modules is 30% and the remainder is assumed to consist of excipients, the same as in the TPC. The second module has a function to provide material and modify the release of API and contains 10 mg excipients. The geometrical volumes of the product variants of CPC range from 4 \text{ mm}^3, the size of a preferred
medication for children assuming a tablet height of 1 mm³ (Klingmann et al., 2013), to 126 mm³, i.e. the volume of the TPC.

The treatment of the patient population is assumed to follow a normal distribution. The dosage need covers the interval from 2.5 to 10 mg, and 99.7% of the treatment need is assumed to fall inside 2.5 and 10 mg. The patient population is generated by using a normal random number generator in MATLAB. One thousand simulations were performed to provide an average population. The treatment of the population with TPC is assumed to be performed in a surplus manner to ensure sufficient dosage; patients requiring a dose i) of 2.5 mg or less are offered a product variant of size 2.5 mg, ii) larger than 2.5 mg but less than or equal to 5 mg are offered a product variant of 5 mg, iii) larger than 5 mg are offered a product variant of 10 mg.

The treatment of the population with the CPC is performed by offering a dose between 2.5 and 10 mg, with a dose step of 0.1 mg (the size of API module). The number of filling modules in each product variant of the CPC follows the assumption; for each dose step that a product variant is configured, product variants exist that are equal with regard to dose but different with regard to the number of filling modules. These product variants, equal in dose content, cover the whole range of product variants when the number of filling modules is varied (inside the allowed product volume region). These variants for respective dosages are assumed to be configured inequal quantities.

The relative value of the CPC compared to TPC is assessed in simulations, where various scenarios, see Table 1, undertake different values on respective in Equation (1). The respective ’s of the CPC are quantified in the following manner: if the value of a VDIV is increased when introducing the CPC the is set to +1 and if the value decreases the is set to -1, an unchanged value is quantified as 0.

**Table 1. Scenarios prepared to assess the relative value of the CPC.**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>W_social</td>
<td>0.67</td>
<td>0.67</td>
<td>0</td>
<td>0.33</td>
<td>0.33</td>
<td>0</td>
</tr>
<tr>
<td>W_ecological</td>
<td>0.33</td>
<td>0</td>
<td>0.67</td>
<td>0.67</td>
<td>0</td>
<td>0.33</td>
</tr>
<tr>
<td>W_economic</td>
<td>0</td>
<td>0.33</td>
<td>0.33</td>
<td>0</td>
<td>0.67</td>
<td>0.67</td>
</tr>
</tbody>
</table>

5 Results from the illustrative case study

This section presents the results from the illustrative case study described in Section 4.

5.1 Sustainability performance assessment of a customized product design

Figure 4 shows the architecture of a customized product design for hypertension treatment. The physical realization of the product is a modularized tablet design. The FR on the highest hierarchical level is provide treatment and realized through the DS tablet. The DS tablet is constrained by size, more specifically volume. The tablet is further
expressed in sub-FRs that the tablet embeds, *treat disease, provide suitable size* and *provide sustained release*. Note that the FRs *provide suitable size* and *provide sustained release* are conceptually realized as a common DS, *filling modules*, hence the physical realization of these FRs are in the same modules.

The DS *API module* to the FR *treat disease* is scalable regarding the number of modules in a product variant. Thus, the platform execution generates a set of product variants consisting of various numbers of modules. These product variants cover each dosage in-between 2.5 and 10 mg, with a dose step of 0.1 mg. Likewise, the DS *filling modules* is scalable according to the number of modules. Varying the number of filling modules provides different sizes of tablets to facilitate administration, which is a known difficulty (Food and Drug Administration, 2015). Additionally, opportunities to tamper with the tablets release properties arise, which are dependent on the size and shape of a tablet (Goyanes et al., 2015). How the release rate is affected is outside the scope of this study.

**5.1.1 Sustainability performance variables**

The execution of the product platform results in measurable SPVs for the CPC. These SPVs are listed in Table 2. Likewise, the SPVs of the TPC have been listed for comparison and follows the assumptions presented in Section 4. As mentioned, the TPC is offered in three variants and an average amount of material consumption is presented. The CPC platform provides 76 feasible product variants by platform execution inside the feasible volume range 4 to 126 mm³. These product variants are described in the number of modules and module sizes, hence the material consumption of variants is calculated from this data. The average material consumption of the whole set is used to enable comparisons.

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*Figure 4. The architecture of the CPC. Adapted from Siiskonen et al. (2018).*

Product design change is the focus of study, hence succeeding life-cycle phases are adopting the nature of the current paradigm. Changes to succeeding phases are logically concluded. For example, an additional assembly process is required to configure an administrable product from modules, the usage of a customised dosage of API is assumed thus, minimizing leftovers during end-of-life and no changes occur to package recycling.
Table 2. SPVs, derived from the SLCA, for the TPC and a CPC.

<table>
<thead>
<tr>
<th>SPV</th>
<th>TPC</th>
<th>CPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design: Nature of design and dimensions</td>
<td>Monolithic design with form of a cylinder with flat faces, ( h = 2.5 \text{ mm} ); ( r = 8 \text{ mm} ); ( V = 126 \text{ mm}^3 )</td>
<td>Modularized design with various forms; Various sizes; Volume range = ([4,126]) mm(^3)</td>
</tr>
<tr>
<td>Raw material: amount, absolute, average[mg/unit]</td>
<td>API: 2.5; 5; 10 - Excipients: 175.4; 172.9; 167.8</td>
<td>API: 2.5 to 10 - Excipients: Varying amounts, scalable property</td>
</tr>
<tr>
<td></td>
<td><strong>Average</strong>: API: 8.2 - Excipients: 169.6</td>
<td><strong>Average</strong>: API: 6.2 - Excipients: 90.7</td>
</tr>
<tr>
<td>Manufacturing: Technologies</td>
<td>Traditional dry powder mixing and compressing in a batch process; (1 manufacturing line, 2 change-overs)</td>
<td>Traditional dry powder mixing, compressing in a batch process; (1 line + 1 change-over, flexible press); + assembly process</td>
</tr>
<tr>
<td>Distribution:</td>
<td>3 SKU</td>
<td>76 SKU</td>
</tr>
<tr>
<td>Use:</td>
<td>User provided with a package of standard dosage of API</td>
<td>User provided with a customised dosage of API</td>
</tr>
<tr>
<td>End of life:</td>
<td>Ideally return leftover doses to recycling/waste treatment, Package to recycling/landfill</td>
<td>Ideally no leftovers Package to recycling/landfill</td>
</tr>
</tbody>
</table>

5.1.2 Qualitative sustainability performance comparison

The qualitative comparison of results in Table 2 are as follows; in the raw material extraction and processing phase, the use of chemicals and solvents, the use of fossil energy and intensive water consumption are examples of issues for the TPC, and a decreased total demand of resources can be expected for the CPC (Slater et al., 2013). In the social dimension, it is likely to encounter issues with work conditions for the TPC, and no change can be expected for the CPC. In the economic dimension, the TPC is associated with challenges concerning various costs for resources and operations, which are likely to decrease for the CPC as a result of a decreased total demand of resources (Slater and Savelski, 2007; Sheldon, 2016). A CPC, based on the assumption that a reduction in material processing is expected, may lead to a reduction of emissions, wastes and water consumption (Unger, 2013; Sheldon, 2016). The social dimension may be associated with workplace challenges in the form of risks for chemical exposure and repetitive work for the TPC (Segawa et al., 2016; Savoia et al., 2017), and no change can be expected for the CPC. The economic dimension is associated with costs for material and operations for the TPC, and increased costs may be expected due to the need of investments in new technology and additional assembly process, and adjustment of information on packages. However, increased innovation capabilities due to the best available technology can be an opportunity.

The distribution phase for the TPC is associated with fossil fuel use and emissions in ecological dimension, which are likely to increase for the CPC due to increased complexity as multiple variants are introduced (Srai et al., 2015). No difference can be expected between the TPC and CPC in the social dimension. The increased complexity may, however, induce increased costs for the CPC compared to the TPC in the economic
dimension. In the use phase, no difference is expected in ecological performance. In the social dimension, the CPC inducing an increased treatment quality is expected (Savoia et al., 2017), but consequently an increased price compared to the TPC. In the economic dimension, an increased price can be problematic from a market attractiveness perspective (Nicholson Price and Rai, 2015).

At the end of life phase, the TPC is associated with linked environmental challenges, including emissions of chemical substances to water and soil, as well as waste management practices of material packaging and surplus dosages (Srai et al., 2015). These challenges are all likely to be decreased for the CPC. In the social dimension, less risk for challenges associated with chemical exposure and societal costs for waste management is expected. The economic dimension is unlikely to change.

5.2 Value chain impact analysis and value modelling
Table 3 summarizes the results from the comparative sustainability assessment and the value chain impact analysis. For each value chain phase, respective VDIVs are listed and categorized according to SD, E- ecological, S-social and $-economic. The CPC is compared to the TPC for each VDIV in each SD. If a VDIV increases, decreases or remains the same (or the change is unknown) with respect to value, the CPC scores a “+”, “-” or “0”, respectively.

Table 3. The VDIV for each value chain phase and the relative value change.

<table>
<thead>
<tr>
<th>Value chain phase</th>
<th>Value driving impact variable</th>
<th>TPC</th>
<th>CPC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>E</td>
<td>$</td>
</tr>
<tr>
<td>Secondary production</td>
<td>Raw material consumption</td>
<td>R</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>Solvent consumption</td>
<td>E</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Investments</td>
<td>F</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inventory</td>
<td>E</td>
<td>+</td>
</tr>
<tr>
<td>Delivery to dispensing point</td>
<td>Transportation</td>
<td>R</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>Packaging cost</td>
<td>E</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>Inventory</td>
<td>N</td>
<td>+</td>
</tr>
<tr>
<td>Dispensing to end user</td>
<td>End-of-life waste</td>
<td>C</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>Unit cost</td>
<td>E</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>Administration effort</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Release properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Side effects</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The results in Table 3 are quantified and plotted for each scenario prepared in Table 1, see Figure 5. For scenarios emphasising social and ecological sustainability, i.e. Scenario 1 and 4, the preferred product design is the CPC. In Scenario 2, where the major emphasis is placed on the social dimension and the second major on the economic dimension, the CPC will still perform better than the TPC value-wise.
6 Discussion

This study has proposed a methodology to conduct value assessments of medicinal products from a sustainability perspective. The selection of guiding questions by Villamil et al. (2018) for the sustainability lifecycle analysis brings difficulty in reproducing the study. The relevant guiding questions for the topic studied has been completely decided by previous experiences, literature, knowledge and interpretations of the researcher. Hence, SPVs describing the TPC and the CPC can be highly varied depending on the researcher performing the study. Future work should include comprehensive studies regarding the selection of the set of guiding questions for medicinal products.

Overall, the proposed methodology is transferable to other products and performed by adapting the product platform to a desired product concept. The transferability to other ODFs, e.g. capsules or liquids, is conducted by adjusting the functioning bandwidths of product platform presented in Figure 4. The methodology can also be applied to medical devices, for instance, an insulin delivery device. An insulin delivery device would consist of insulin and a device providing the means of administering the insulin. The architecture of the insulin delivery device can be established by adjusting the architecture of tablet, see Figure 4. The treat disease FR on the second hierarchical level can be solved by the API system DS (referring to insulin in a realizable form). On the lowest hierarchical level, various types of insulin can be generated by introducing bandwidths to the DSs. Further, the provide suitable size FR can be generally expressed as provide convenient drug delivery, hence expanding the functional bandwidth beyond a tablet. Thus, the FR can be solved by the insulin delivery device DS and physically realized as various types of devices. Platform execution generates various insulin - insulin delivery device variants and the compatibility to patient attributes can be increased through medication adherence. The number of successful treatments can increase and the value of VDIVs in the social and economic SD. Poor adherence of diabetes medication has shown to be a major cost for health care due to for example hospitalisations (Ho et al., 2006).

Figure 5. Relative value of CPC compared to TPC for each scenario prepared in table 1. Revisiting the research question ‘How is the value chain affected from a sustainability perspective due to an introduction of customized product design?’ can be stated that in the value chain, value is created for scenarios emphasizing social and environmental sustainability. An introduction of a CPC leads to reduced API consumption and reduced side effects because of an elimination of surplus dosing. Surplus dosing with the TPC is an assumption and the API consumption can be overestimated. Excipient
consumption decreases due to the scalability of the number of filling modules and constraining the maximum product volume of the CPC.

A flexible size and shape are assumed to decrease administration effort and enhance release properties. The freedom of scaling the number of filling modules, covering the whole feasible product variant volume range, is considered a valid opportunity. The sizes of the TPC variants are the same regardless of dose content and hence, it is assumed that the API to excipient ratio is not optimized for the TPC. A traditional production process is assumed to remain the same but the adjustability of a tablet press to the considerably smaller module size of a CPC is not verified and need further investigation. Further, solvent consumption needs to be studied when elaborate studies on production processes are performed.

The CPC is assumed to better match the medication demand, which entails a shift from a high to low inventory environment, both in the secondary production- and delivery phase. This shift increases value from an economic perspective. The unit cost of the CPC will increase, hence becoming less affordable and value destructive from a social perspective. Each VDIV in the value model is judged equally important within an SD. A comparison regarding the better or worse performance of the CPC to the TPC is provided but the magnitude is not given. Thus, scales to rate the VDIVs according to should be implemented. For the respective SDs, the VDIVs are judged equally important, e.g. the VDIV unit cost and reduction of side effects, in the social dimension, are both given the same absolute quantity. A patient might have a higher willingness to pay for a product eliminating side effects, which should be emphasized more. Thus, internal weightings should be introduced.

7 Conclusions and future work

The proposed methodology shows that a value-driven approach can be used to support systematic decisions regarding medicinal product designs. The methodology adopts a full sustainability perspective and provides opportunities to study effects on the whole value chain of pharmaceutical products. However, conducting the sustainability performance assessment of product concepts is highly governed by researchers’ experiences, knowledge and available literature, hence complicating the reproducibility of the study. Future studies on sustainability performance criteria of medicinal products need to be conducted. Additionally, this method will be expanded in the future to enable the assessment of various new product concepts on more elaborate quantitative scales. Furthermore, internal weightings of VDIVs in respective sustainability dimension should be introduced to emphasize VDIVs considered to be more important. The proposed methodology can be transferred to products beyond the ODF, shown conceptually on a medical device.

Data show that: A CPC is preferable if value is to be created from a social or/and an environmental sustainability perspective.
**Acknowledgements**

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Matilda Watz
Utilizing requirements to support sustainable product development


The attention to sustainability impacts arising during the lifecycle of products is growing as industry wants to increase its contribution to a sustainable society. To do so, companies must find ways to navigate the complexity of the needs within the socio-ecological system in which they operate. In engineering design projects, the interpretation of needs into requirements is essential, as they represent the collective understanding of the design problem to be solved. Ideally, requirements are possible to verify and validate, which makes it challenging for industry to integrate socio-ecological considerations, often based on qualitative models, into requirements. Sustainability then tends not to be prioritized in trade-offs with traditionally identified requirements for engineering design.

A qualitative research approach within design research methodology framed a sequence of studies guided by the research question ‘How can requirements be utilized to support Sustainable Product Development?’ First, a research gap was identified from a literature review which indicated a lack of socio-ecological systems contextualization in the identification, as well as the traceability of sustainability criteria to integrate into requirements. Secondly, a conceptual model was established for how management of requirements can be improved to facilitate traceability, as well as how contextual socio-ecological systems perspective can be introduced in the selection, of sustainability criteria for engineering design projects. For this purpose, the results from a multiple-case study based on semi-structured interviews with seven design and manufacturing companies was triangulated with findings of an in-depth literature analysis. Five key elements of management of sustainability in requirements were proposed in a profile model corresponding to different levels of sustainability maturity. A third study explored, based on literature and prototype causal loop diagramming, the potential of a group model building approach to enhance contextual understanding of strategically identified, i.e., company-tailored, sustainability criteria in relation to traditional requirements in early phases of the product innovation process. A final study investigated how a strategic sustainability perspective can be integrated with engineering design methods and value modelling to create a decision support for concept selection.

The studies together indicate that key constituents of good requirements, traceability and systems contextualization, can be achieved also for socio-ecological sustainability considerations. This requires organizational commitment and will be reflected in the design of the operational management system for their product innovation process. Following the proposed five key elements of sustainability integration in requirements, a company is expected to increase the organizational sustainability maturity, and hence its capability to contribute to a sustainability transition. This research also shows that there is a gap in current methods and tools for enhanced socio-ecological systems contextualization. The two last studies of this thesis give promising approaches of tools and methods to be further developed and analyzed, namely group model building, system analysis and value modelling.