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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.

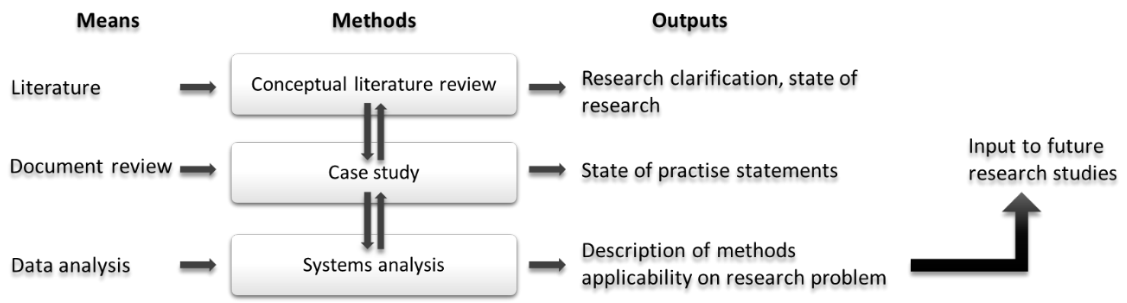

Figure 1. Methods used in the study.

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).

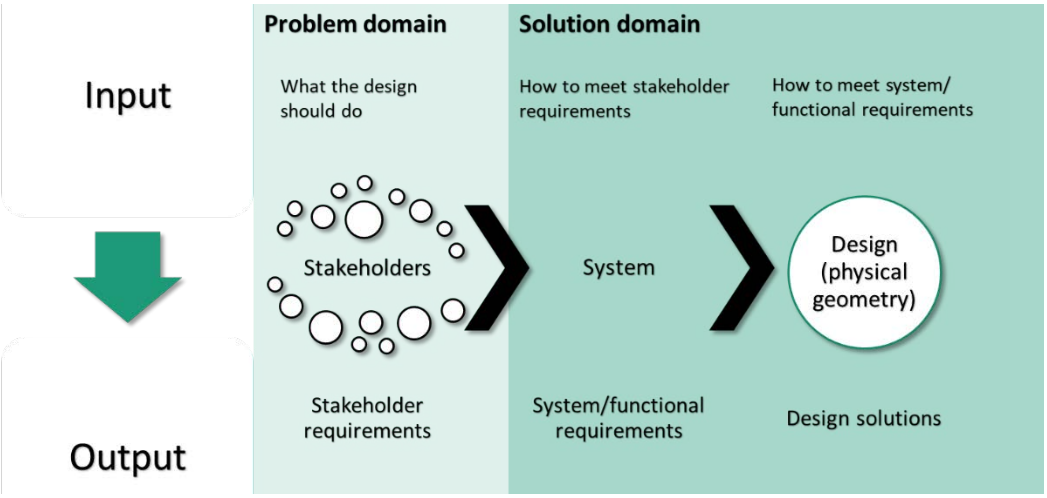

Figure 2. The process starts with problem identification on an overall level to solution generation on a detailed level.

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).

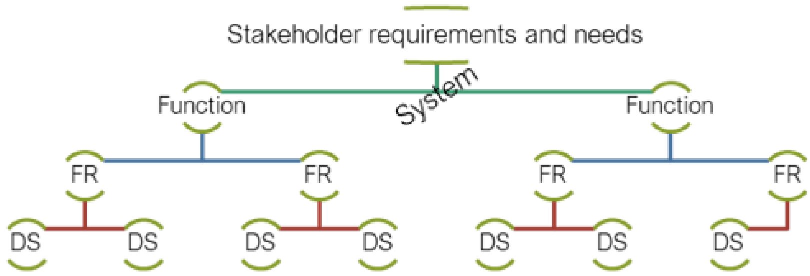

Figure 3. Example of a requirements architecture, displaying connections between stakeholder requirements and needs, functions, functional requirements (FR) and design solutions (DS).

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 fulfil 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)

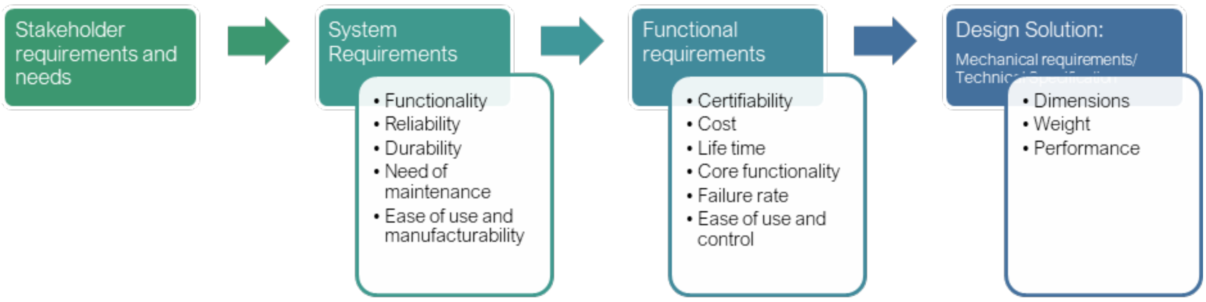

Figure 4. Examples of requirements on different levels in the requirements architecture.

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 (Niccoló 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 adaptions 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).

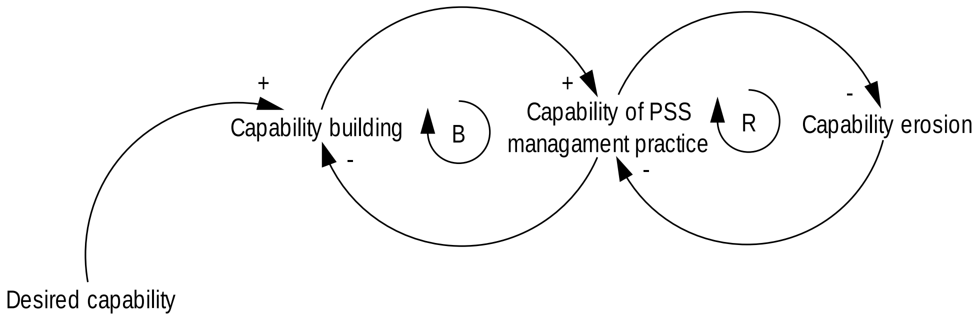

Figure 5. Causal Loop Diagram of the fundamental feedbacks for the building and break-down of capabilities. Adopted from Rodrigues et al. (2017).

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 6. The same authors also presented potential indicators to measure the capability of an organisations 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.

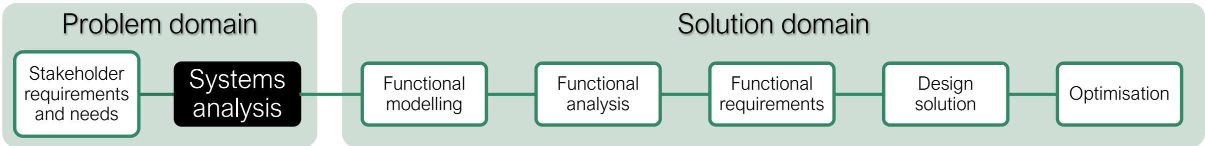

Figure 6. Potential location for systems analysis in the requirements engineering process.

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 2.

Table 1. Leading sustainability criteria and -indicators

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

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 2 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.

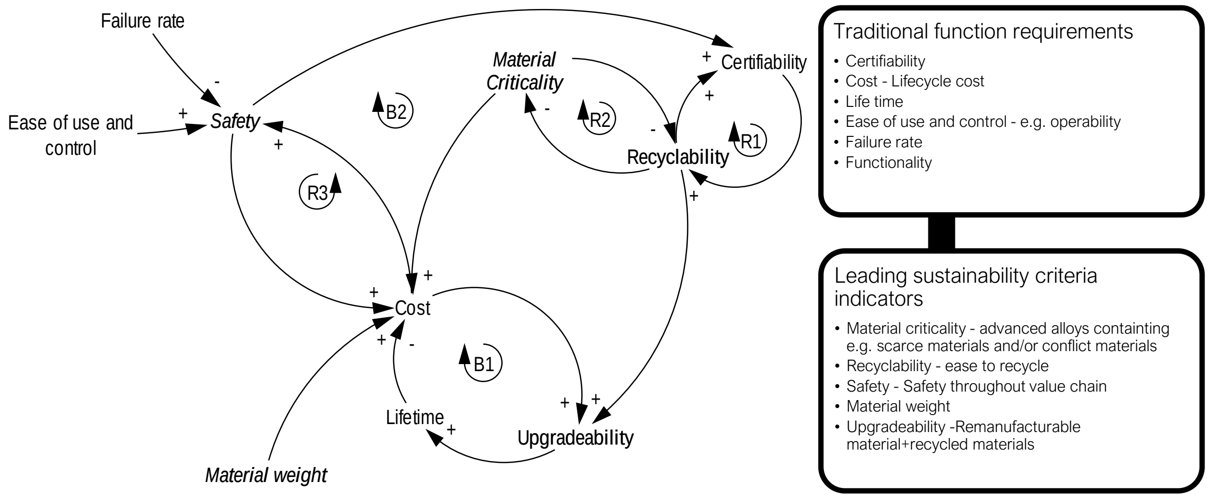

Figure 7. A simplified CLD was developed to test how to visualise trade-off- and opportunity relations between leading sustainability criteria and traditional design requirements.

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).

6 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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