



## State of the Art of Design Methods for Resource Efficient and Effective Solutions

– Report from “Product and Service Design Methods for REES”  
Project of Mistra REES program

**Authors:** Sergio A. Brambila-Macias, Sara Nilsson, Maria Widgren, Mattias Lindahl and Tomohiko Sakao

**Affiliation:** Division of Environmental Technology and Management, Department of Management and Engineering, Linköping University

**Submission date:** 28<sup>th</sup> of April 2017

**ISRN Number:** LIU-IEI-RR--17/00264—SE

**Contact:** Tomohiko Sakao (tomohiko.sakao@liu.se), Project Manager

## **Acknowledgment**

This research was supported by the Mistra REES (Resource Efficient and Effective Solutions) program, funded by Mistra (The Swedish Foundation for Strategic Environmental Research).

## Table of Contents

<b>1</b>	<b>Summary .....</b>	<b>5</b>
<b>2</b>	<b>Introduction .....</b>	<b>6</b>
	2.1 Goal and scope .....	6
	2.2 Method .....	6
	2.3 How to use this report .....	6
	2.4 Report structure .....	6
<b>3</b>	<b>Identified current use .....</b>	<b>7</b>
	3.1 Requirement specification .....	7
	3.1.1 Types of requirements and sources .....	7
	3.1.2 What Information is required to create the specification and how it is found .....	7
	3.1.3 Considered environmental requirements .....	8
	3.1.4 Are requirements a must to achieve, or only wishes? .....	9
	3.1.5 Prioritization of requirements .....	9
	3.1.6 Communication of requirements .....	9
	3.1.7 Methods to derive and manage requirements .....	10
	3.1.8 Discussion .....	11
	3.2 Conceptual design .....	11
	3.2.1 Overview .....	11
	3.2.2 The interaction of actors in conceptual design .....	11
	3.2.3 How are requirements used in conceptual design? .....	13
	3.2.4 Methods used during conceptual design .....	13
	3.2.5 Discussion .....	14
	3.3 Analysis and evaluation .....	14
	3.3.1 Overview .....	14
	3.3.2 Methods from literature .....	15
	3.4 Entire early stage .....	18
<b>4</b>	<b>Derived requirements .....</b>	<b>20</b>
	4.1 Requirement specification .....	20
	4.1.1 Types of requirements and sources .....	20
	4.1.2 What Information is required to create the specification, and how is it found? .....	20
	4.1.3 Considered environmental requirements .....	20
	4.1.4 What is considered that is not in the requirements specification? .....	20
	4.2 Conceptual design .....	21
	4.2.1 Introduction .....	21
	4.2.2 The interaction of actors in the development process .....	21
	4.2.3 How are requirements used in the conceptual design? .....	21

4.2.4	Methods used in conceptual design .....	22
4.2.5	Discussion .....	22
4.3	Analysis and evaluation .....	23
4.4	Entire early stage.....	25
5	Conclusion .....	26
6	References.....	27
<b>Appendix 1 - The method used for searching the relevant literature .....</b>		<b>32</b>
<b>Appendix 2 - The questions asked in this review and references useful for the questions.....</b>		<b>33</b>
<b>Appendix 3 - Definitions .....</b>		<b>39</b>

## 1 Summary

This document reports on the results of work packages (WPs) 2.1 and 2.2 in Project 2 (Product and Service Design Methods for REES, i.e. resource efficient and effective solutions) of the Mistra REES program ([www.mistrarees.se](http://www.mistrarees.se)). WP 2.1 and WP 2.2 aim at documenting current use of design methods and deriving requirements for design methods, respectively. The document only covers results from the scientific literature review, while other reports to be developed will cover results, for instance, from the interview study and the design session with industry partners in the Mistra REES consortium. The results of the literature review will be a foundation for WP 2.3, which aims at developing new design methods. Note that methods here include frameworks, tools, and support for designers.

The document describes current use (i.e., “as-is” status) of product and service design methods when designing REES, as well as requirements for product and service design methods for REES (i.e., information soon-to-be). Both of these are results of analysis in different phases of an early phase of design for REES. Those phases consist of requirement specification, conceptual design, and analysis and evaluation, which can be ordered temporally along the design process.

From the overall analysis, found is a lack of insights about methods for designing REES, although potentially useful methods are available. This means advancement of knowledge is insufficient for industry within the subject, which is relatively new. It may also mean the developed methods are not precisely according to the needs of companies. This shows a high potential of developing new methods in the rest of the project.

More specifically, in the requirement specification, the literature shows that potentially useful methods include QFD (Quality Function Deployment), the Taguchi method, the Kano model, and data mining, among others. In the conceptual design, numerous methods exist, and most of them were developed in an older context, where REES was not as relevant as today. Those methods include DfX methods (X denotes cost, assembly, etc.), the functional block diagram, the checklist, morphological analysis, and the Fishbone Diagram. Only a few seem to be used widely in industry today. In the analysis and evaluation, available methods include Lifecycle Simulation, Lifecycle Costing, multi-criteria decision making, and the Analytical Hierarchy Process. Most of the methods or tools available specialise in one area. This is a problem when developing an integrated offering of products and services, because designers need to have a holistic perspective for that.

Regarding requirements for methods to be developed, the authors analysed literature as follows. In the requirement specification, requirements originating from multiple aspects and actors need to be taken into account. Since an enormous amount of data and information can be collected from products and by technologies implemented today, a huge opportunity is presented for enhancing requirement specification. Yet, there seems to be little insights to take this opportunity. In conceptual design, it is important to identify and involve relevant actors as well as their requirements according to a number of scientific reports. Especially, interaction between the relevant actors seems to be critical to be implemented. In analysis and evaluation, various pieces of earlier research works recommend different features to be implemented in methods. These features include visualization of information and information flows, graphical user interface, multiple users’ participation, and ability to handle environmental information, uncertainty and risk.

## **2 Introduction**

### **2.1 Goal and scope**

This document aims to report the latest insights about design methods for REES reported in the scientific literature. The insights include the methods used in industry and what requirements exist for methods. The target readers are industry partners from the manufacturing sector in the Mistra REES consortium. The target design methods are used in an early phase of design of products and/or services as well as for resource efficiency and effectiveness. The types of products and services are not specific, and thus the reported insights are applicable to a broad range of sectors.

### **2.2 Method**

The method adopted is based on a systematic literature review. This involved identifying relevant literature in international scientific journals via predefined keywords (the so-called literature pool) as stated in Appendix 1 and analysing the identified literature. This analysis included adding other relevant literature that was referred to in the literature pool or the authors were aware of. This method aimed to ensure covering both classic and contemporary literature in design for REES. In addition, predefined questions were adopted to search relevant literature in the analysis as shown Appendix 2. This ensured a comprehensive coverage of the interesting issues. As a base for the analysis, several key terms were defined as shown in Appendix 3.

### **2.3 How to use this report**

This report is prepared for the partners and, in particular, the manufacturing companies in the Mistra REES program. For them, there are two main ways to use the report. First, it can be used as a handbook. This means that it is not necessary to read every page; rather, one can search for specific information in this report, e.g. available methods for requirement specification for designing REES. Second, by reading the report in full, it can be used to learn more about the state of the art of methods for REES in the entire early stage of design.

### **2.4 Report structure**

The remainder of the report is structured as follows. Sections 3 and 4 describe the methods used in industry today, and what requirements exist for those methods, respectively. Each of Sections 3 and 4 consist of four sub-sections: requirement specification, conceptual design, analysis and evaluation, and the entire early stage. The first three sub-sections correspond to the order within the early-phase design, and are followed by the overall description of the early phase. Section 5 concludes the report.

### 3 Identified current use

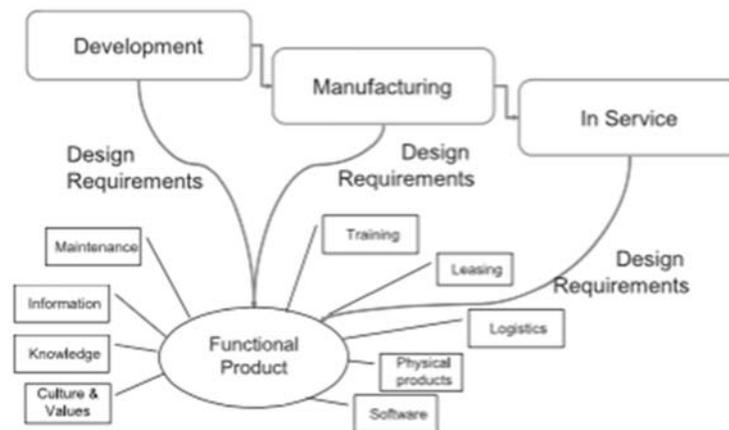
#### 3.1 Requirement specification

##### 3.1.1 Types of requirements and sources

Here are some sources that are used to derive requirements:

- Customer (Azadi and Saen, 2013; Brown, 1991; Chen et al., 2011; Ghahramani and Houshyar, 1996; Ghahramani and Wang, 1998; Sadek and Welp, 2009; Song et al., 2013; van der Merwe et al., 2015)
- Cost (Azadi and Saen, 2013)
- Sustainability (Cocca and Ganz, 2015)
- Environment (Luttropp and Lagerstedt, 2006)
- Maintenance/service (Crowder et al., 2012; Goffin, 2000; Wong et al., 2008)
- Manufacturing (Ghahramani and Wang, 1998; Vianello and Ahmed-Kristensen, 2012)

Maussang et al. (2009) propose a methodology “with the whole system’s requirements as precise as possible for the development of the physical objects involved in those systems. Furthermore, Maussang et al. (2009) highlight that an integrated offering is influenced by several factors that are not necessarily included in traditional product development. Isaksson et al. (2009) mention some examples of things that need to be considered when moving toward offerings from a traditional product, namely “easy to maintain, upgradeable, with built-in sensors for collecting in-use and service data, and easy to use”. **Figure 1** represents an overview of their view on what is included in functional sales.



**Figure 1. Representation of properties in a functional product.**

Looking at the product lifecycle design, it requires simultaneous consideration of product functionality, manufacturability, assemblability, serviceability, reusability and recyclability (Gu and Sosale, 1999).

Most literature focuses on how to involve customer needs. Ullman (2002b) talks about customer requirements, where these also include manufacturing and other aspects that make the customer include more aspects than only the user. Attempts to organize as much information as possible in the realization process of a product is referred to by Dixon and Poli (1995) as concurrent design, with approaches such as Design for X, where X can stand for anything related to the product and its lifecycle.

##### 3.1.2 What Information is required to create the specification and how it is found

Methods from integrated product service systems and traditional product development most often consider customer needs and translate these into functional requirements. Safety, cost, strength,

manufacturing and other aspects should be considered to complement the customer needs. This section gives additional information on what aspects and actors are important in the development process of the requirements specification. Customer requirements are e.g. found by interviews, focus groups or surveys (Ulrich and Eppinger, 2000). Information from other areas can come from e.g. benchmarking or visual mapping.

Several different information systems are developed and explained in the literature. A reflection after this literature review is that the most common information type discussed is getting feedback from maintenance and service during the use phase back to the designer in the development phase. Ashworth et al. (1996) developed software to manage product data for a range of engineering requirements, which as mentioned earlier is essential for an integrated offering. Another software application, developed by Hvam et al. (2013), shows the improvements in the requirements specification from using their product configuration system where information about the product is collected. They also present four cases with industrial application, but only describe the benefits, and not how the system is used in detail.

In a similar field, Ghahramani and Wang (1998) describe a systems engineering approach with which to process manufacturing information through identifying critical relationships between the manufacturing process and manufacturing system characteristics (product or service attributes that judge its productivity, timeliness, cost and quality) by evaluating what is essential and where to focus resources.

Several authors try to utilize information from maintenance or service activities in order to design offerings that should be easier to maintain. Goh et al. (2009) focus on using records from maintenance and service as a source of information, and change the earlier semi-structured method of collection to a more structured one to facilitate learning from in-service experience. Igba et al. (2015) argue that in-service data can be used and sent back as feedback to the early stages of the product lifecycle. Their framework is developed from the point of view of an integrated product and service provider, where data mining is used to identify relevant information. Jagtap and Johnson (2011) use information from in-service when redesigning aero engines in a movement towards functional sales. Wong et al. (2008) use front-line maintenance data documents as a source of knowledge about how maintenance issues need to be handled in the early design. Crowder et al. (2012) developed a large hypermedia-based Knowledge Desktop to support maintenance and future design. In this software application, ontological hypertext is used to guide the engineer towards the relevant information needed from service actions.

From a lifecycle point of view, Heisig et al. (2014) developed an information system that captures information about e.g. a product, process or rationale to support different lifecycle phases. Shu and Wang (2007) identify key elements of product lifecycle modelling to integrate all the information from a product lifecycle and support the networked manufacturing mode.

### **3.1.3 Considered environmental requirements**

Most of the literature about requirements for integrated offerings does not mention environmental requirements at all, but rather has an economic focus. Cocca and Ganz (2015) see this "sustainability trend" as a marketing opportunity, and therefore included these aspects in the development process. They studied the different environmental aspects that were considered in some eco-labels, and from there created a set of requirements such as waste, wastewater, emissions, infrastructure and resource consumption. Luttrupp and Lagerstedt (2006) present what they call ten golden rules as a generic way of incorporating environmental aspects into product design. Even though this paper focuses on physical products, it should be of interest for the development of integrated offerings.

Maintenance is the most common aspect to look at in order to extend an offering's lifetime. Closer links to environmental issues were been found in the reviewed literature.

#### **3.1.4 Are requirements a must to achieve, or only wishes?**

As found in the literature about traditional product development, requirements can be set with different prioritisations and severity. An example can be demands and wishes, where demands must be met and wishes should be taken into consideration (Cross, 1989; Pahl et al., 2006). Others use the terms requirements, criteria and desired functions (Andreasen et al., 2015b; Andreasen and Hein, 2000). Here, requirements must be applied to the solution, criteria represent qualities or properties that help demonstrate if a solution is good or bad, and the desired features are attributes that possibly could contribute to the value of the solution. Requirements can however be of different importance, and some aspects that do not have to be fulfilled can still affect the design, e.g. personal experiences or what manufacturing processes to use. Many decisions are in the hands of the designer regarding the most beneficial design choice, and determining if these aspects should be included as requirements. It is also important to bear in mind the design freedom for the designer. Everything cannot be constricted with requirements; there will always be some freedom in choices that affect the outcome. In some of the literature, the authors refer to aspects to consider but do not define them to be included within the requirements. For example, lower environmental impact can be set in the requirements, but how much or what environmental issue to focus on is not defined.

All customer needs cannot be quantified, but they still need to be considered in the design process (Ullman, 2002b). For example, the strength of a specific component can be set but the type of material to be used cannot, so other aspects will affect the choice of material; perhaps manufacturing equipment that is available could be important. Chen et al. (2011) use QFD to assist designers in linking customer requirements and manufacturing processes during product development, thereby enhancing customer satisfaction and increasing manufacturing efficiency. The manufacturing process in this case is not seen as a requirement, but rather only an aid to fulfil customer requirements.

#### **3.1.5 Prioritization of requirements**

Ghahramani and Houshyar (1996) use QFD to represent prioritization of customer needs. Brown (1991) also uses QFD to represent prioritization of the voice of the customer but with a more specific four-step process, namely product planning, component deployment, process planning, and production planning. Azadi and Saen (2013) use data envelopment analysis together with QFD by imprecise enhanced Russell graph measures for incorporating criteria such as cost of services and ease of implementation in QFD. Chen et al. (2011) propose a product design methodology that integrates the grey relation approach to QFD and quality engineering (QE) to incorporate aftermarket service with the Taguchi method.

Some other methods for prioritization include e.g. Goffin (2000), who uses cost models to guide decisions that may have to be made about trade-offs between features, manufacturability and supportability. Song et al. (2013) created a tool based on Group AHP and rough set theory to facilitate prioritizing requirements. Berkovich et al. (2014) use their model for structuring requirements, enabling traceability, and finding conflicts, which facilitates prioritization and gives an overview of what impact the prioritization has.

#### **3.1.6 Communication of requirements**

Communicating a common understanding of a product is essential to reduce misunderstandings that could be costly and cause overrun the development process. Several information systems have been developed to provide information to different actors within the system and centralize where information from different actors or lifecycle stages can be found. Ashworth et al. (1996) use STEP (an ISO standard for the Exchange of Product Model Data), and show how it could be used for sharing information between involved actors and to support a range of engineering requirements. Ghahramani and Houshyar (1996, p. 1) take the advantages of QFD and use it as a means for communication between interdepartmental groups in the product development teams, e.g. as design, manufacturing, marketing and the final user of the product.

Another approach is presented by Crowder et al. (2012), who use ontological hypertext to extract and give the right and relevant information from service activities to the designer. In a similar way, Wong et al. (2008) present software that examines and analyses relevant information for the involved actors, which facilitates knowledge sharing between these actors. Another software application was developed by Goh et al. (2009) with a mapping system to categorize maintenance cases to facilitate information sharing with design engineers. Jagtap and Johnson (2011) present a framework as a communication tool between designers and service providers that makes it easier for the designer to extract in-service information that can help in the redesign of components or systems of the existing product. All of this software allows the user to quickly find highly relevant information.

Heisig et al. (2014) have proposed a list of core and candidate information categories (e.g. component/part, rationale, parameter, design process, and constraint) to use as a basis for information and knowledge sharing for both external and internal communication. Ming et al. (2008) propose a framework for product lifecycle collaboration to achieve better customer-centric products and services. Shu and Wang (2007) offer a framework for product lifecycle modelling and discuss how a product lifecycle information model helps a manufacturer to make decisions about management, design, production, operation, maintenance, and repair. van der Merwe et al. (2015) describe an integrated value proposition design framework to align all stakeholders around the customer instead of the product, as in traditional product lifecycle management. They argue that their framework, with a combination of structure, process and people, can be used as a planning and communication tool.

### 3.1.7 Methods to derive and manage requirements

QFD is definitely the method that is mentioned the most within the reviewed literature (Azadi and Saen, 2013; Brown, 1991; Büyüközkan and Berkol, 2011; Chen et al., 2011; Ghahramani and Houshyar, 1996; van der Merwe et al., 2015).

Some other methods mentioned are:

- Taguchi method (Chen et al., 2011)
- Data mining (Goh et al., 2009; Igba et al., 2015)
- Kano model (van der Merwe et al., 2015)
- Blue Ocean Strategy (van der Merwe et al., 2015)
- Knowledge Desktop, based on ontological hypertext (Crowder et al., 2012)
- Manufacturing information process, an approach to process manufacturing information through analysis of relationships by evaluating what is significant and where to allocate resources (Ghahramani and Wang, 1998)
- DFS, design for supportability (Goffin, 2000)
- Scenarios, to describe actions between the offering and the user and actions inside the offering between the included elements to identify needs and wishes (Maussang et al., 2009)
- Web-based integration framework (Shu and Wang, 2007)

Two authors have developed methods specialised for developing integrated offerings.

Song et al. (2013) developed a tool that considers the interaction of different stakeholders and helps to generate the IPS2 requirement from the perspective of lifecycle and customer value. In the proposed model, integration of a rough set analytic hierarchy process method is applied and deals with subjectivity and vagueness in an effective way for the selection of requirements. *Sustainability or resource effectiveness and efficiency* are however not included as an obvious input at the moment.

Berkovich et al. (2014) propose a requirements data model (RDMod) for integrated product and service offerings. This model describes different types of requirements and the relations between them. It especially addresses issues with structuring, enabling tractability, and finding conflicting requirements. This

method was developed from a software and system modelling point of view, with little focus on sustainability and resource-efficient and effective aspects in the offering's development.

### **3.1.8 Discussion**

The literature shows that most methods or tools today specialise in one area or another, even though an integrated offering needs to have a holistic perspective. Some methods exist for structuring the prioritization, but no general trend can be shown regarding what type of requirements are considered the most important. Different authors highlight different aspects, and it is important to investigate the industry's perspective.

Management systems can be used for such things as structuring, enabling tractability and finding conflicting requirements. The requirements need to be integrated in the early stages of the development process in order to have a high impact on the final result. One single type of aspect or requirement is not the most likely to be the hardest to fulfil, rather conflicting requirements that create trade-off issues between them are the complex requirements to meet. Cost and quality, for example, often have a correlation.

## **3.2 Conceptual design**

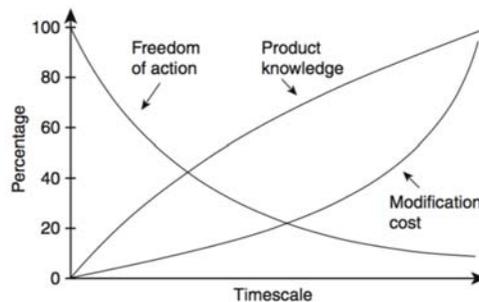
### **3.2.1 Overview**

Based on authors like Andreasen and Hein (1987); Hansen and Andreasen (2003); Roozenburg and Eekels (1995); Ulrich and Eppinger (2011b), conceptual design is a phase in the design process in which activities focusing on determining principal proposals, i.e. concepts (including products or services), are to be carried out. It implies that the concepts are brought up to such a level of concretisation and completeness that they include all necessary means for realising the functionality of the concept. Furthermore, it suggests that the description of the concepts allows someone to communicate to others the most important and distinguishing aspects of the concepts (and included products and services), and how they will satisfy the identified requirement specification.

In the following section, "actors" is an overall term used to describe different stakeholders, partners, and so on. This section is divided into three parts: the first is about actor interaction in the conceptual design; the second, about how requirements are used in the conceptual design; and the third, about methods used in the conceptual design.

### **3.2.2 The interaction of actors in conceptual design**

Concept generation is a creative process where different innovation stimulating methods are used to produce many new potential concepts, for both new and older problems (see e.g. Ulrich and Eppinger (2011b)). The conceptual design phase has a high impact on the final performance of the product (Lindahl, 2005; Lindahl and Sundin, 2012; Ullman, 2002b); sometimes called the design paradox, this is illustrated in Figure 1. If relevant actors are involved too late in the process, the result is less optimal concepts, and/or in the fact that work will have to be redone, something that normally is costly. Time spent on incorporating relevant actors, not only in developing a well-founded requirements specification but also in resulting concepts, will be recovered later in the development process (Lindahl and Sundin, 2012).



**Figure 2. Illustration of the design paradox** (Lindahl and Sundin, 2012).

The main actors of a business-to-business relationship are identified as the customer, the OEM (also known as the product and service provider), suppliers (module, product, and service supplier), and society (e.g., government and competitors), in relation to sustainable and ecological solutions (Meier et al., 2010a). However, the conceptual design involves many different actors. Sampson and Spring (2012) describe eight actors from the traditional manufacturing supply chain, namely component suppliers, labour, design engineers, production managers, product managers, quality assurance managers, inventory managers, and competitors.

According to Uflacker and Zeier (2011), it is generally accepted that when developing and creating innovative concepts they should be promoted by a user-centric and outside-in driven design focus. Therefore, the degree to which a design team interacts and involves external actors, such as by talking to customers, end users, and domain experts, presents an interesting aspect in the observation of conceptual design (Uflacker and Zeier, 2011). Interacting with customers is interesting as long as they do not just focus on what Geelen et al. (2013) mention: that some end-users will be most interested in the lowest cost, while for others different motivations may be dominant, such as comfort and environmental concerns. In a study by van der Merwe et al. (2015), customer opinions were collected at an early stage of the process through a refined Kano model, and then translated by means of the QDF matrix in every step of the process.

Selviaridis et al. (2013) suggest that a more nuanced conceptualisation of the notion of sourcing capabilities could be that these do not necessarily reside in the buying company, but that they could be developed through interactions with suppliers and third parties instead. Customers mainly create value through relationships and service experiences in service-dominant offerings, which is stated in as well as evolved from the marketing perspective (Aitken et al., 2006; Vargo and Lusch, 2004).

In order to identify relevant actors and establish the inbound roles of actors and information flows within a conceptual design, a mapping system is of good use (Desai et al., 2015; Tan, 2010). Yin and Ma (2012) bring up the term “feature parameter map”, which is a conceptual organisation scheme for modelling dependencies between parameters. Yin and Ma (2012) continue to describe these feature parameter relations as a lower level of detailed information than features, but they are intended as a means to manage parametric relations and the consistency of the overall design model during the conceptual design.

van der Merwe et al. (2015) introduce a different approach to product lifecycle management (PLM) by shifting the primarily product-centric focus to a customer-centric one through defining an engineering framework of processes, principles, and methods, and by introducing key concepts with multifunctional team integration and business process parallelisation. According to Counsell and Puybaraud (2006), there is a need for more research to be able to find a distinction among the various needs and modes of work of different actors, and to look at both at them as individuals and in the aspect of collaboration.

### 3.2.3 How are requirements used in conceptual design?

Requirements are the foundation for the conceptual design. Conceptual design is described by (Wang et al., 2002) to be dominated by the generation of ideas, which are thereafter evaluated against the criteria of the general requirements.

In traditional conceptual design (see e.g. Roozenburg and Eekels (1995) and Ullman (2002a)), the main focus is on the conceptual design of products, and little or no concern is given to related or potential services. Traditionally, services have been designed and added on, not only after the product is designed but also after it is produced (Tukker and Tischner, 2006a).

In order to realize the planned concepts' lifecycle, the design team is expected to define the requirements for the design and the lifecycle flow design as a result of lifecycle planning (Umeda et al., 2012). Design requirements are composed of and logically specified from the statement of the problem to be solved (Yin and Ma, 2012). For the design of appealing as well as sustainable services, it is important to meet the requirements of various actors simultaneously (Watanabe et al., 2012).

Agost et al. (2006) discuss how models and patterns are neither static nor universal. On the contrary, within a dynamic and collaborative process they must be reviewed, discussed, modified, and enriched to be able to fit the needs and specific requirements.

### 3.2.4 Methods used during conceptual design

Andreasen et al. (2015a) state that methods play a large role in facilitating team dialogue and creating shared understanding. During the last three decades, numerous methods have been developed in order to support the conceptual design of product service systems and similar approaches. Andreasen et al. (2015b) discuss a risk in projects where specific tools, methods, standard procedures, and standard documentation dominate the practice. They continue by stating that this leaves no choice for the designer regarding how to work, since the tools and methods may "arrange" the daily work to such an extent that their own reflections on the appropriateness of e.g. a method's use become redundant.

Numerous methods used during conceptual design are described in the literature, and the role of a method or tool varies widely (Andreasen et al., 2015a). To support the assessment of communication patterns, foster the temporal relationships between different actors and information resources over the course of collaboration, and provide a live view into the online communication activities of conceptual design teams, Uflacker and Zeier (2011) applied team collaboration networks (TCN) as a model in eleven distributed engineering design projects.

Another method used during collaboration is collaboration moderator services (CMS), which helps in the identification, acquisition, maintenance and evolution of knowledge, and which supports effective knowledge sharing including raising awareness about possible consequences of actions and of other actors' needs during the collaboration (Swarnkar et al., 2012).

Shah et al. (2000) describe intuitive methods in a five-category sub-classification: germinal (used when there are no existing concepts), transformational (used to generate ideas by modifying existing ideas), progressive (ideas are generated by repeating the same set of steps a number of times), organizational (used to help organize the ideas that have been generated), and hybrid (combine many different techniques to address varying needs at different phases of idea generation).

Umeda et al. (2012) describe how conceptual design from a lifecycle perspective implies the application of DfE methodologies (DfR, DfDA, DfRM, DfRU, DfMod). The WordTree method is described by Moreno et al. (2014) as a Design-by-Analogy method that provides a structured approach for re-representing design problems, and also for identifying potential analogies and analogous domains.

Finally, even though many methods exist to support conceptual design, the literature shows no sign of any wider use of them in industry. Reported are mainly single tests of methods, and some examples of case studies. Other methods used for conceptual design found in the literature include:

- AREP (A compact Internet-centric product assembly representation) – represents a collection of assembly features to constrain the design assemblies assigned to individual designers, and further to form a whole collaboratively developed assembly (Xu and Liu, 2006)
- Collaborative Interactive Applications Methodology (CIAM) implies adopting different viewpoints for creating conceptual models of systems (Molina et al., 2005)
- Corporate planning system (CPS) is the extent of conscious utilization of specific methods to forecast the future of small and medium-sized enterprises depending on objective and subjective factors (Solesvik, 2006)
- Germinal Methods, Morphological Analysis, Brainstorming and the K-J Method (Shah et al., 2000)
- Hierarchical Task Analysis (HTA) – a complete and detailed list of tasks related to the specific activity that will be tested and of the physical/operational and cognitive/cultural “abilities” requested of users to do them (Di Bucchianico et al., 2012)
- Hybrid Method, Synectics (Shah et al., 2000)
- Kano technique, Quality Function Deployment (QFD), Life Cycle Assessment (LCA), Design for X (DfX), Design for Disassembly (Sakao and Shimomura, 2007)
- Knowledge-Based Engineering (KBE), Methodology for Knowledge-Based Engineering Applications (MOKA) (Agost et al., 2006)
- Multiple-case study method – provides a stronger base for theory building (Eisenhardt and Graebner, 2007)
- Organizational Methods, Affinity Method, Storyboarding, and Fishbone Diagrams (Shah et al., 2000)
- PCN Analysis – studying service supply chains (Sampson and Spring, 2012)
- Progressive Methods, Method 6-3-5, C-Sketch, and the Gallery Method (Shah et al., 2000)
- The functional block diagram (FBD) is a tool to model and analyse a PSS structure. It is flexible, requires a minimum of details on the concept elements, gives a lot of information to start a study, can accommodate a wide range of systems and can be comprehended during the conceptual design (Maussang et al., 2009)
- Transformational Methods, Checklists, Random Stimuli, and the PMI Method (Shah et al., 2000)

### 3.2.5 Discussion

The interaction of actors in the conceptual design is quite traditional and mainly focused on those related to classical product sales business models. The main focus is on the traditional customer. The same traditional approach is found when looking into how requirements are used in the conceptual design.

There are numerous methods to support conceptual design; according to the literature, however, very few seem to have reached any wider use in industry. Understanding why this is the case and determining how to increase the use of these methods will require additional research.

## 3.3 Analysis and evaluation

### 3.3.1 Overview

According to Sim and Duffy (2003), the activities belonging to evaluation activities in the design process include decision making, evaluating, selecting, analysing, modelling, simulating and testing/experimenting. One could argue that some of these activities are used interchangeably in the engineering design literature, since few authors have attempted to distinguish them. Some important mentions, however, are Hazelrigg

(1998) in a practical manner and Gero (1990) and Gero and Kannengiesser (2004) in a more theoretical way.

According to Gero (1990), analysis deals with the behaviour of objects while evaluation is a comparison between alternatives. One can therefore think of analysis as the prediction on how an artefact (product, service or system) may behave according to a set of determined criteria (reliability, sustainability, costs, flexibility, feasibility, etc.) (Gero and Kannengiesser, 2004; Hazelrigg, 1998). Evaluation, in turn, can be understood as the means by which one can compare alternative concepts (Dieter and Schmidt, 2013).

Furthermore, the literature in analysis and evaluation can be divided into methods that describe the current practice and those that suggest possible ways to analyse and evaluate design. These could be classified into descriptive and prescriptive methods. Descriptive methods focus on current practices, while perspective methods propose a "could be" or "to be" approach. In this section, some of the descriptive methods are presented; these are usually those found in industrial practice. Additionally, descriptive methods for PSS design are also found in later sections.

### 3.3.2 Methods from literature

Bieda (1992) provides a Life Cycle Cost (LCC) methodology that presents quantitative estimates for design feasibility for the early phase of design. It focuses on warranties as well as the impact of changes (sensitivity) on reliability, repair costs and purchase costs. According to the author, LCC helps to promote teamwork between the engineering and business community. Moreover, Cheaitou and Khan (2015) tackle multi-criteria decision making, or MCDM, with qualitative and quantitative factors to select suppliers. They also make use of AHP and optimization to rank and select suppliers according to specific criteria. Gatenby et al. (1994), in turn, present why and how to implement Concurrent Engineering (CE) along with how to transform an organization (business unit in this case) into CE. They provide a guideline based on case studies in seven steps:

1. Benchmark and Performance targets: Provide a clear vision for the project/improvement to be made.
2. Breakthrough improvement: Allocate resources to achieve the project.
3. Characterize current process: The team needs to gain knowledge about current processes.
4. Create the target process: Create a realistic plan.
5. Verify new processes: Select a pilot project to validate the new processes.
6. Implement across product lines: the pilot is extended.
7. Measure results and improve: continuously monitor the improvements.

Gatenby et al. (1994) also present barriers to CE (commitment, culture, organization, technology). Moreover, they provide a good definition of CE. A widely accepted definition of CE was published in 1988: *"CE is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the product developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements"*

Furthermore, Garetti et al. (2012) conducted a state-of-the-art review of existing solutions implementing Life Cycle Simulation (LCS). They provide four guidelines or preferred characteristics for LCS: modularity, stochastic behaviour of models, LCC and social and environmental impacts. Most Industrial applications of LCS have been in facility management, industrial robot manufacturing, welded joint ship structures, emissions, cement manufacturing, and electronics, among others.

In a similar fashion, Georgiadis et al. (2013) highlight the importance of defining clearly the problem domain before turning to the solution domain. The authors conducted an extensive literature review on decision-making methods, and mention the importance of the work of T.L. Saaty and the Analytical

Hierarchy Process (AHP), which is used for selecting among alternatives, especially in the early phases of design. The figure below shows some of their extensive literature. The authors also highlight the importance of systems engineering and sensitivity analysis in decision making. They also highlight the technique for order of preference by similarity to ideal solution (TOPSIS). They argue for the use of rigorous methods when conducting Analysis of Alternatives (AoA) in the context of the Department of Defence (DoD) in the USA.

**Table 1. MCDM models**

<b>MCDM Models</b>	
Simple Additive Weighting (SAW) or Weighted Sum Method (WSM)	(Fishburn, 1965), (Fishburn, 1967), (Afshari, et al., 2010)
Weighted product model (WPM)	(Triantaphyllou, et al., 1998), (Wang, 2011)
Analytic Hierarchy Process (AHP)	(Saaty, 1980, 2008), (Nydick & Hill, 1992), (Barzilai & Golany, 1994),
Revised Analytic Hierarchy Process (AHP)	(Belton & Gear, 1983), (Holder, 1990), (Triantaphyllou, et al., 1998)
Analytic network process (ANP)	(Saaty, 1996, 2004), (Triantaphyllou, et al., 1998), (Yang, et al., 2008)
Multi-attribute utility theory (MAUT)	(Keeney & Raiffa, 1993), (Keeney, 1975), (Fülöp, 2005), (Butler, et al., 2005)
Multiple Attribute Group Decision Making (MAGDM)	(Kim, et al., 1999).
Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)	(Yoon, 1980), (Hwang & Yoon, 1981), (Triantaphyllou, et al., 1998)
ELimination and Choice Expressing Reality (ELECTRE)	(Roy, 1991), (Fülöp, 2005), (Triantaphyllou, et al., 1998), (Figueira, et al., 2005), (Roy & Vanderpooten, 1996)
Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE)	(Brans, et al., 1986), (Brans & Vincke, 1985), (Vincke, 1992), (Hopfe, 2009)
Geometrical Analysis for Interactive Aid (GAIA)	(Brans & Vincke, 1985), (Vincke, 1992)
Superiority and inferiority ranking method (SIR method)	(Xu, 2001)
Potentially All Pairwise Rankings of all possible Alternatives (PAPRIKA)	(Hansen & Ombler, 2009)

Another publication that looks at different methods for decision making in engineering design is provided by the National Research Council Committee (2001) in the USA (a national institution providing advice on key issues). In their report, they propose that decision making in engineering design can be addressed through decision analysis as a form of applied decision theory. The Council suggests that the purpose of decision analysis is to provide decision makers with clarity of their actions in an uncertain environment. Moreover, the council argues that a good decision is based on outlining three elements, namely alternatives, information available and preferences of the decision-maker. The report provides a summary of tools for decision making, which are presented below.

The National Research Council proposes the above categories as a discussion platform, arguing that not all are actual tools, but some are more frameworks or operational philosophies, as is the case of concurrent engineering. Nevertheless, the committee suggests that not all tools will cover all aspects of decision making or design, and that value provided is in their applicability. Furthermore, Chen et al. (2012) also make an important contribution in what is known as decision-based design, which builds upon decision theory. The authors advocate for integrating consumer preferences into engineering design through a more rigorous approach.

With regard to product/service systems (PSSs), most methods are general and rarely specifically address the analysis and evaluation of conceptual design. Methods in this area of research find inspiration from knowledge coming from a mix of disciplines, namely marketing, engineering design, operations management and information technology. QFD, FMEA, DfX, Pugh's Total Design, TRIZ, Taguchi methods, and fuzzy theory are some methods found in the literature. In PSSs, Service CAD by Komoto and Tomiyama (2008) and Service Explorer by Sakao and Shimomura (2007) are some examples of analysis and evaluation. Integrated product and service design processes by Aurich et al. (2006) as well as fast-track total care

design by Alonso-Rasgado et al. (2004) are also design methods for PSSs. Heterogeneous IPS2 by Meier and Massberg (2004) is worth mentioning, as these authors attempt to model PSS. The design process for the development of an integrated solution by Morelli (2002) is also an important contribution.

**Table 2 Tools used in decision making in engineering design (adapted from NRC 2001).**

Tools		Primary Basis						Ratings by the Committee (1=low; 5=high)				
Approach	Tool Name	Knowledge Engineering	Logic/Set Theory	Matrix Algebra	Probability	Statistics	Economics	Current Utilization	Concept Creation	Concept Development	Selection Among Alternative Concepts	Ease of Use
Practical	Concurrent Engineering						X	4	2	4	4	1
Qualitative	Decision Matrix			X			X	4	1	2	4	5
	Pugh Method			X				3	4	5	1	2
	QFD			X				2	2	4	2	1
	AHP			X				3	1	2	4	
	Product Plan Advisor	X		X	X			3	2	3	4	3
Statistical	PLS				X	X		1	3	3	2	1
	Taguchi Method				X	X		4	1	4	4	2
	Six Sigma				X	X		3	3	3	3	2
Creative	AI Support	X						2	4	2	2	2
	TRIZ	X						3	3	1	1	3
Axiomatic	Suh's Theory		X	X				2	2	3	5	1
	Yoshikawa Theory		X					1	1	1	1	1
	Math Framework		X		X	X	X	1	1	1	5	3
Validating	Game Theory				X		X	1	1	1	3	2
	Decision Analysis		X		X		X	3	1	4	5	3

Furthermore, the literature addressing economic and environmental evaluation in design includes Lindahl et al. (2014), who make use of case studies in order to quantify environmental and economic benefits of the Integrated Product Service Offering (IPSO) in real practice. The authors use three companies (paper mill plugs, cleaning of buildings, and soil compactors) to present different scenarios/offerings and compare them through Life Cycle Costs (LCC) and Life Cycle Assessment (LCA). These scenarios show different possible outcomes for companies implementing IPSOs, and hence provide a tool to make decisions that are more informed.

Finally, Wrisberg et al. (2002) conduct a thorough review of analytical environmental tools for environmental design and management. Their contribution is part of the European environment and climate programme CHAINET, carried out between 1997 and 1999. The figure below shows their review in a concise manner, as well as the tools reviewed in their publication. These tools include LCA, ERA, SFA, CBA, MFA and checklists as described in the figure.

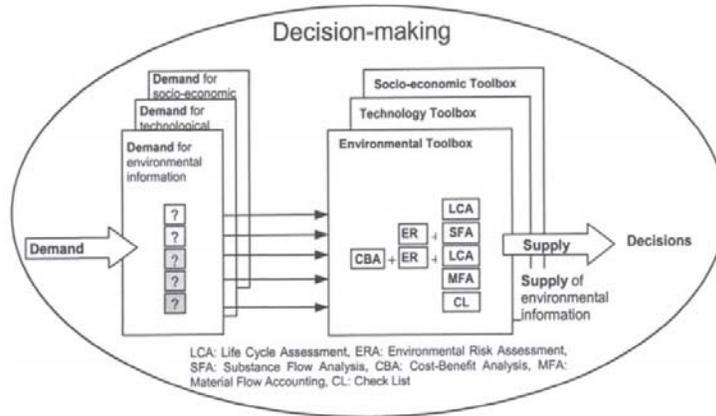


Figure 3. Analytical tools for environmental design.

### 3.4 Entire early stage

Development processes can look different, depending on the company. The process defines steps and activities from planning until release (Ulrich and Eppinger, 2000). Two common processes can be seen in Figure 4. Both Ulrich and Eppinger (2011a) and Pahl et al. (2006) follow a fairly similar process, beginning with planning and goal clarification, continuing with setting requirements, then generating concepts, evaluating concepts, detailed design and finally preparing for production. Early stages of the development process have a high impact on the final performance of the developed concept (Dixon and Poli, 1995; Ullman, 2002b).

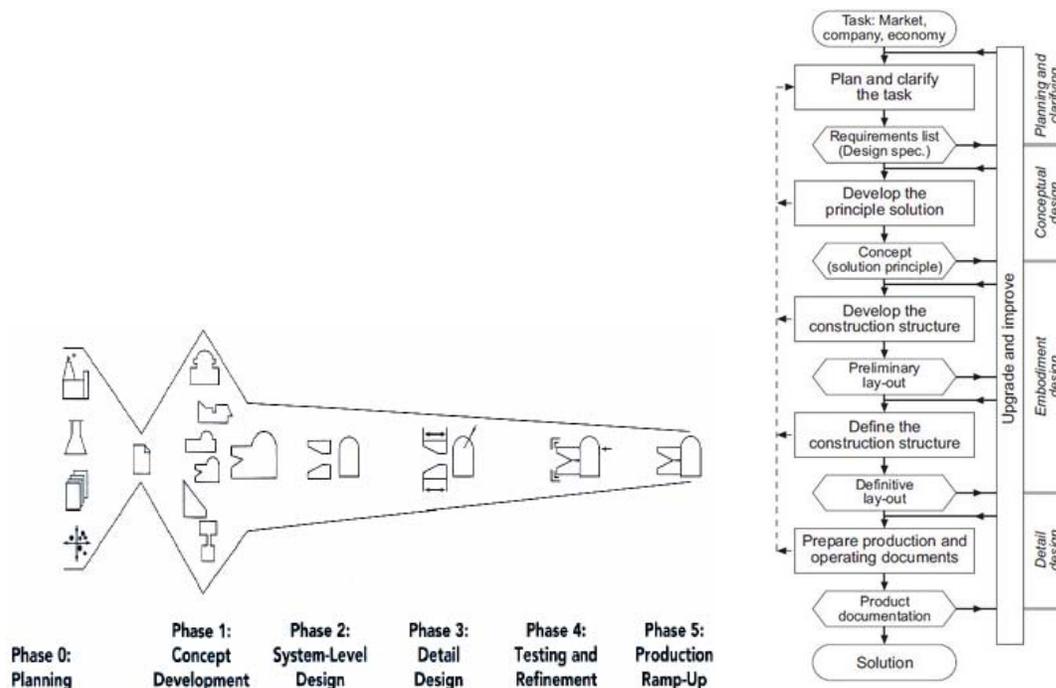


Figure 4. Product development process suggested by Ulrich and Eppinger (2011a), to the left, and Pahl et al. (2006), to the right.

These development processes mainly focus on traditional product development, but since most integrated product service offerings are emerging from a physical product, the development process is still affecting how offerings are developed (Meier et al., 2010a)(Sakao and Lindahl, 2012). Neither focus on resource efficiency and effectiveness to the same extent as e.g. Design for Environment methods, which specialise in environmental aspects (Schott et al., 1997).

## **4 Derived requirements**

### **4.1 Requirement specification**

#### **4.1.1 Types of requirements and sources**

An integrated offering consists of combinations of physical products, services and systems that have been integrated and optimized from a lifecycle perspective in relation to customer value (Meier et al., 2010a). This creates a complexity with requirements originating from several different aspects, and actors that need to be considered (Vasantha et al., 2012). The integration and collaboration with stakeholders and actors offerings is, according to e.g. (Vasantha et al., 2012) and (Mont, 2002), seen as an important aspect of creating a successful offering.

#### **4.1.2 What Information is required to create the specification, and how is it found?**

Research has been done in the area of who and what to consider in the requirements specification, but no clear signs of industrial implementation is found in the literature.

Vianello and Ahmed-Kristensen (2012) argue that today, very little knowledge about changes is transferred to the next generation of products, and they present a framework for how to collect information from the manufacturing and installation process and take this information into consideration for future generations. This is also emphasized by Isaksson et al. (2009), who mention e.g. in-use and in-service data as sources of information.

Berkovich et al. (2011) highlight that an offering consists of various components such as physical products, software and services, all of which traditionally work differently with requirements. Therefore, all involved actors from various domains also need to be involved and considered when deriving requirements for an offering.

#### **4.1.3 Considered environmental requirements**

Durugbo (2013a) lifts sustainability, technical ability and marketability as three components in an offering, where the underpinning expectation is to "lower environmental impact in comparison to a more traditional transaction" where value is created in "use of environmentally friendly technologies that optimise the use (or function) of goods and services" and contribute to "dematerialization for functional economies".

Directions and standards can also be used to help determine what environmental issues need to be considered, e.g. the European Union's Ecodesign Directive (Directive 2009/125/EC), REACH, ERP, ROHS, and ISO standard 14006.

#### **4.1.4 What is considered that is not in the requirements specification?**

Cocca and Ganz (2015) mention that an integration of green services in the portfolio offers the opportunity to create an additional customer benefit and to increase customer satisfaction. The way they suggest it, environmental consideration could be achieved without having environmental aspects specifically included in the requirements specification. In a similar thought, Maussang et al. (2009, p. 364-365) state "..., the evaluation of PSS solutions from an environmental, economic and technical point of view is crucial to ensure enterprises to switch largely to these solutions", but these mentioned categories are not clearly used when setting requirements for the integrated offerings in the proposed methodology.

## **4.2 Conceptual design**

### **4.2.1 Introduction**

In Section 4.2, actors are an overall term used to describe different stakeholders, partners, etc. This section is divided into three parts. The first part is about actor interaction in the conceptual design; the second is about how requirements are used in the conceptual design; and the third is about methods used in the conceptual design.

### **4.2.2 The interaction of actors in the development process**

Innovation-stimulating methods and requirements (highlighted in the previous section) alone are not enough to develop potential concepts. Also needed is a spectrum of different actors, which based on their own perspectives and experiences, can manipulate and use these innovation-stimulating methods and requirements to develop new potential concepts.

Even though not clearly highlighted by early authors like Asimow (1962) and Roozenburg and Eekels (1995), later authors, e.g. Ulrich and Eppinger (2011b), Tidd et al. (2005), and not least Hippel von (2005) and Chesbrough (2010), stress the importance of involving external actors. Hippel von (2005) stresses the involvement of intermediate users (individual end users or user communities) and companies. He further stresses that this is essential because products are developed to meet the widest possible need. Often, customer innovators share their ideas with product developers in hopes of having them develop the product they need.

In line with Hippel von (2005), Chesbrough (2010) highlights what he calls open innovation, a concept that refers to the use of both inflows and outflows of knowledge to improve internal innovation and expand the markets for external exploitation of innovation (Cheng and Huizingh, 2014). The core idea is that, in a world of increasingly widespread knowledge, concept designers cannot rely solely on their own concept design, but should instead buy or license processes or inventions from other actors.

This implies that the modern interpretation is that conceptual design involves many different actors, who view the process from different perspectives, including professionals such as engineers, designers, and planners and non-specialists such as customers and users (Bouchlaghem et al., 2005).

Based on the literature, the importance of involving relevant actors in conceptual design seems to increase when it comes to the conceptual design of PSSs and REES (see e.g. Charter and Tischner (2001); Kindström and Kowalkowski (2014); Kowalkowski et al. (2009); Neugebauer et al. (2012); Sakao (2011); Tan (2010); Tukker (2004); Tukker and Tischner (2006b)). Actors normally not involved in the value creation become part of it, and it is therefore often essential to keep them involved in the conceptual design in order to incorporate their perspectives and experiences, and to stimulate new potential concepts.

### **4.2.3 How are requirements used in the conceptual design?**

Lee et al. (2006) highlight the importance of looking to requirements derived from concurrent engineering principles and best practices in order to realize a collaborative design and process planning. van der Merwe et al. (2015) also stress the importance for an organisation to meet requirements on a desired level in order to keep their customers satisfied. Several authors, e.g. Lee et al. (2006), stress that the development team members should look across multiple disciplines to identify various requirements.

As stated in the previous chapter, traditionally, services have been designed and added on, after the product is not only designed but also produced (Tukker and Tischner, 2006a). According to the design paradox, this is not a very suitable approach (Lindahl and Sundin, 2012). Instead, in order to develop more resource-efficient and effective products, in the conceptual design, the concept's ingoing products and

services should be developed in an integrated and parallel manner (Meier et al., 2010b; Sakao and Lindahl, 2015; Tan, 2010; Tukker and Tischner, 2006a).

Ming et al. (2008) propose a framework for product lifecycle collaboration in order to respond to new business requirements for effective collaboration during the entire product lifecycle. Lee et al. (2006) state that there are three key requirements to consider: “previous sequential working procedures need to be broken down and redefined before conceptual design planning in a collaborative and parallel manner; the establishment of an interdisciplinary development team aims at the coordination of decisions in the early stage of product development; and an early consideration of a design decision on manufacture can lead to the avoidance of expensive changes during later lifecycles.”

Selviaridis et al. (2013) state that providers of services play a key role when defining what is procured, and how they step in and help buying firms specify their requirements.

According to Zeng et al. (2011), designers need to take four ergonomic design dimensions into account to develop highly innovative, competitive products and services – functionality, safety, usability, and effectiveness – in order to achieve high-order organisational objectives. Zeng et al. (2011) continue by stating that creativity becomes the key to simultaneously addressing different design requirements caused by the four ergonomic design dimensions. These are fundamental objectives or strategic goals that the organisation intends to accomplish, and they will define the general context of design for the organisation (Zeng et al., 2011).

#### **4.2.4 Methods used in conceptual design**

As stated earlier, Andreasen et al. (2015a) stress that methods play a large role in facilitating team dialogue and creating shared understanding. However, Andreasen et al. (2015b) also note a risk in projects where specific tools, methods, standard procedures, and standard documentation dominate the practice. According to these authors, it is important that actors have the time and freedom to reflect upon the methods used in the conceptual design. For example, are the methods used appropriate, or could other ones be more useful?

#### **4.2.5 Discussion**

The conclusion based on the literature (e.g. Charter and Tischner (2001); Kindström and Kowalkowski (2014); Kowalkowski et al. (2009); Neugebauer et al. (2012); Sakao (2011); Tan (2010); Tukker (2004); Tukker and Tischner (2006b)) is that when developing PSSs and REES, it is important to identify and involve relevant actors and their requirements in the conceptual design. Shimomura et al. (2013) describe the interactions between actors as the critical factor for improving customer satisfaction, and that PSS providers are therefore required to include and organise human resources from the viewpoint of “customer” requirements.

Methods for supporting the identification of relevant actors and establishing their inbound roles seem to be useful and needed.

Based on the literature, there still seems to be a quite traditional way in how requirements are used in the conceptual design process. Requirements are first used to develop the concepts’ ingoing products, and once that is finalized, they are used for developing the concepts’ ingoing services. However, several authors (e.g. Meier et al. (2010b); Sakao and Lindahl (2015); Tan (2010); Tukker and Tischner (2006a)) stress the importance of requirements being used for an integrated and parallel conceptual design of a concept’s ingoing products and services.

### 4.3 Analysis and evaluation

This section presents more prescriptive methods ("could be" or "to be" methods) in analysis and evaluation. The literature shows these methods have been applied in case studies, but are not widely used in industry. Some of these methods are provided below.

Bertoni et al. (2015) propose a method for decision making that reinforces the need to move from intuition-based decision making to evidence-based regarding sustainability. The authors make use of modelling of a value chain with respect to sustainability in order to support decisions in the early stages of design in the aerospace industry. They propose a tool to visualize where value is added in a design. Different colours show how different components can add value to the design. Moreover, Brad (2009) makes use of a modified version of QFD for multivariate optimization. The author combines TRIZ and algorithms with QFD, and proposes a Concurrent Multi-function Deployment method, or CMFD. This method harmonises product planning and product design when facing multiple-objective functions. The author suggests that the CMFD method supports "design for excellence".

For their part, Buxel et al. (2015) make use of LCA as a management tool for decision making in five areas:

1. Strategy development
2. RD and product development
3. Supplier selection and production
4. Marketing and sales
5. Information, training and education

They also show how to successfully do it (avoid complexity, decide if internal or external actors should perform the LCA, aim at targeted audiences, ensure efficiency and ensure top management support). Moreover, Chen et al. (1998) call for an integrated design environment for concurrent engineering through an integrated graphical user interface (GUI). They advocate that in concurrent engineering, a software application/tool is needed that several people can access at the same time in order to reduce time and cost when designing.

Chou (2014), in turn, provides a rich introduction regarding eco-design. Many definitions of eco-design currently exist; Chou suggests that it can be understood as a systematic process that integrates environmental aspects in the early phases of design. According to Chou, eco-design can be categorized into eight goals: (1) reduction of the number of different materials and selection of the most appropriate ones; (2) reduction of environmental impact in the production phase; (3) optimization of the distribution phase; (4) reduction of environmental impact in the use phase; (5) extension of the product's useful life span; (6) simplification of product disassembly; (7) design for reuse; and, (8) design for recycling. The author also classifies the techniques developed into guidelines/standards, checklists, comparative tools, and analytical methods. Chou (2014) then introduces the ARIZ method (algorithm for inventive problem solving) as a combination of the TRIZ method and Life Cycle engineering (LCE) model as a holistic method. The use of ARIZ includes restructuring new product concepts, assessing alternatives and refining engineering options.

In a similar fashion, De Benedetti et al. (2010) developed a method based on key environmental performance indicators (KEPIs) and the Cambridge Engineering Selector CES database for an eco-audit tool. This tool seems to be more for management than engineering, and for use in the very early stages of design. Another tool, or rather a method, which can also be considered more managerial, is proposed by Bach et al. (2016). Their method, called ESSENZ, provides comprehensive measures for the resource efficiency of products, processes and services. The authors integrate 21 categories to measure the impact on the environment, the economy and society, and suggest that this method has been well received in case companies.

Regarding decision making, Dekkers (2000) addresses decision models for outsourcing and how to link them to a manufacturing strategy. According to the author, few approaches exist for decision making for outsourcing which take core competencies into consideration. Their method combines process mapping with decision making, comparing processes with technological and performance criteria. These processes are pre-design, design, engineering, manufacturing engineering and manufacturing. The decisions made in the different processes identify core competencies and the additional ones needed to complete the supply chain. This is done at three levels, the strategic, tactical and operational.

In regard to the evaluation of information, Manley (1996) presents a method called the Object Transformation Process Model (OTPM) to determine useful data for different departments at a company. It discusses quality of information and how to obtain and analyse it. OTPM helps engineers in identifying the minimum essential information (MEI) needed to plan, direct, control, evaluate, and continuously improve information about any process. This paper addresses information flow analysis and how to “filter” data by also taking into account that communication is difficult due to experiences, culture, jargon and background.

Nixon (1999), in turn, reviews the literature and two case studies to look at performance in design and its contribution to business performance. This paper explains what design is in general, and its importance for companies and even for the wider context in the world. The authors argue that performance indicators can move from more strategic to more operational. However, if companies want cash flows in the early stages of design, this might be too early and difficult to provide. One problem is that design is a multi-disciplinary activity; another is that design is a term with many different meanings. Also, as the authors suggest, “An apparent contradiction exists in the literature. Survey results show that managers regard the design and development of new products as the single most important factor for future company performance, yet there is a good deal of evidence to indicate that it is uncommon for design managers in both the USA and the UK to have a major influence on strategy formulation” (p 818). Finally, this paper proposes the following assumptions on p 818 regarding design:

- 1) “design is crucial to innovation and is central to competitive, functional and corporate strategies;
- 2) design is a multi-dimensional activity that interacts in different ways with customers, technology, research, finance, marketing, distribution and logistics as well as information technology;
- 3) performance measurement of design can support decisions relating to design management expenditure and outsourcing, and design management in an operational and strategic context”

In terms of modelling, Durugbo (2013a) and Durugbo (2013b) use different tools to model flows of information, and then use SysML. The figure below shows the modelling by flow used by Durugbo (2013a).

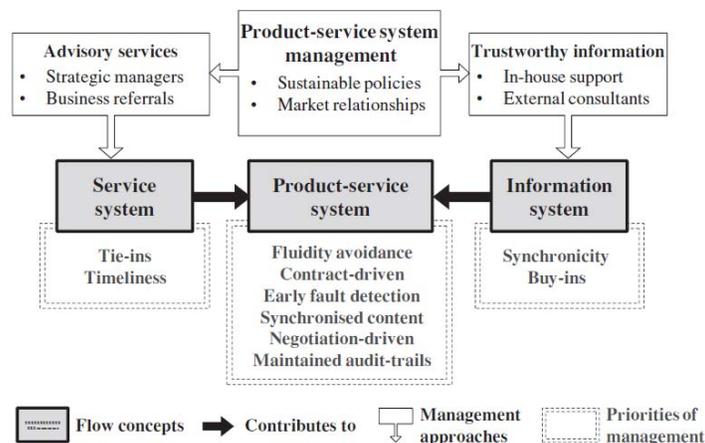


Figure 5. Information flows (Durugbo 2013a)

Some authors address uncertainty in design; those relevant to PSSs include Erkoyuncu et al. (2014), who use soft systems methodology and case studies to present a framework to manage uncertainty on cost estimates. Their framework is comprised of seven stages, namely plan, identify, prioritize, classify, and manage cost uncertainties. Their framework supports companies in the defense sector in the UK in project planning, uncertainty visualization, and capability management. The authors score and prioritize different types of uncertainties (quantitative and qualitative) in order to help in identifying and prioritizing cost uncertainties.

The distinction of analysis, evaluation and decision making is not clearly defined in the literature. In the larger engineering design community, contributions from Hazelrigg (1998) and Gero (1990) provide insights into the differences between these activities. With regard to environmental tools, the literature shows that among those tools used are LCA, environmental risk assessment, MFA and checklists. In PSSs, this has been addressed by Lindahl et al. (2014), while Ercoyuncu et al. (2014) have addressed risk and uncertainty as relevant topics. It is also fair to suggest that no one tool will solve all problems, and a combination of tools is advisable when tackling decision making, analysis and evaluation in the early stages of design, depending on the problem at hand.

#### **4.4 Entire early stage**

The type of sequential design or development that could be captured in e.g. Ulrich and Eppinger (2011a) and Pahl et al. (2006) is rare in industry in general regardless of if the design is for REES or not. In reality, a more dynamic process with iterations and retakes is common. A part of these iterations and retakes is caused by non-optimal set-up, design procedure, organization and/or management and thus should and can be removed. However, to realize circular flows of materials in our societies and get maximum value out of the used resources, product and service design needs to be more dynamic by e.g. including more communication and collaboration among various actors both internally and externally: reuse, maintenance, refurbishment, and remanufacturing all requires some information to be shared between relevant actors. Design methods are also expected to facilitate more communication and collaboration.

## 5 Conclusion

According to the systematic review of scientific literature, a numerous number of design methods exists in the literature. Some of them are meant for design methods for REES and are potentially useful in industry. However, the literature gives no clear sign of those scientifically validated methods being used widely in industry today. This shows a high potential of the project aiming at developing scientific design support or methods for REES to be used widely in industry.

Concerning requirements for design methods for REES, the literature recommends various features to be implemented. Those features include ability to address multiple aspects and actors that are relevant to REES, to identify and involve relevant actors as well as their requirements, to visualize information, and to handle environmental information, uncertainty and risk.

Future work in this project of Mistra REES program includes deriving requirements for design methods for REES based on interview with companies as well as protocol analysis of experienced practitioners' designing activities. Further, development and validation of new support or methods will be carried out in the project.

## 6 References

- Agost, M.J., Romero, F., Vila, C., 2006. Use of patterns for knowledge management in the ceramic tile design chain, International Conference on Cooperative Design, Visualization and Engineering. Springer, pp. 65-74.
- Aitken, R., Ballantyne, D., Osborne, P., Williams, J., 2006. Introduction to the special issue on the service-dominant logic of marketing: Insights from The Otago Forum. *Marketing theory* 6, 275.
- Alonso-Rasgado, T., Thompson, G., Elfström, B.-O., 2004. The design of functional (total care) products. *Journal of Engineering Design* 15, 515-540.
- Andreasen, M.M., Hansen, C.T., Cash, P., 2015a. *Conceptual Design*. Springer.
- Andreasen, M.M., Hansen, C.T., Cash, P., 2015b. *Conceptual design: Interpretations, mindset and models*. Springer International Publishing.
- Andreasen, M.M., Hein, L., 1987. *Integrated Product Development*. IFS Publications Ltd., Bedford, UK.
- Andreasen, M.M., Hein, L., 2000. *Integrated Product Development*. IPU, Denmark, Europe.
- Ashworth, M., Bloor, M.S., McKay, A., Owen, J., 1996. Adopting STEP for in-service configuration control. *Computers in Industry* 31, 235-253.
- Asimow, M., 1962. *Introduction to design*. Prentice-Hall, Englewood Cliffs, N.J.
- Aurich, J.C., Fuchs, C., Wagenknecht, C., 2006. Life cycle oriented design of technical Product-Service Systems. *Journal of Cleaner Production* 14, 1480-1494.
- Azadi, M., Saen, R.F., 2013. A combination of QFD and imprecise DEA with enhanced Russell graph measure: A case study in healthcare. *Socio-Economic Planning Sciences* 47, 281-291.
- Bach, V., Berger, M., Henßler, M., Kirchner, M., Leiser, S., Mohr, L., Rother, E., Ruhland, K., Schneider, L., Tikana, L., 2016. Integrated method to assess resource efficiency—ESSENZ. *Journal of Cleaner Production* 137, 118-130.
- Berkovich, M., Leimeister, J.M., Hoffmann, A., Krcmar, H., 2014. A requirements data model for product service systems. *Requirements Engineering* 19, 161-186.
- Berkovich, M., Leimeister, J.M., Krcmar, H., 2011. Requirements engineering for product service systems: A state of the art analysis. *Business and Information Systems Engineering* 3, 369-380.
- Bertoni, M., Hallstedt, S., Isaksson, O., 2015. A model-based approach for sustainability and value assessment in the aerospace value chain. *Advances in Mechanical Engineering* 7.
- Bieda, J., 1992. A PRODUCT-CYCLE COST-ANALYSIS PROCESS AND ITS APPLICATION TO THE AUTOMOTIVE ENVIRONMENT. *Proceedings Annual Reliability and Maintainability Symposium*, 422-425.
- Bouchlaghem, D., Shang, H.P., Whyte, J., Ganah, A., 2005. Visualisation in architecture, engineering and construction (AEC). *Automation in Construction* 14, 287-295.
- Brad, S., 2009. Concurrent multifunction deployment (CMFD). *International Journal of Production Research* 47, 5343-5376.
- Brown, P.G., 1991. QFD - ECHOING THE VOICE OF THE CUSTOMER. *At&T Technical Journal* 70, 18-32.
- Buxel, H., Esenduran, G., Griffin, S., 2015. Strategic sustainability: Creating business value with life cycle analysis. *Business Horizons* 58, 109-122.
- Büyükköçkan, G., Berkol, C., 2011. Designing a sustainable supply chain using an integrated analytic network process and goal programming approach in quality function deployment. *Expert Systems with Applications* 38, 13731-13748.
- Charter, M., Tischner, U., 2001. *Sustainable Solutions - Developing products and services for the future*. Greenleaf Publishing Limited, Sheffield, UK.
- Cheaitou, A., Khan, S.A., 2015. An integrated supplier selection and procurement planning model using product pre-design and operational criteria. *International Journal of Interactive Design and Manufacturing - Ijidem* 9, 213-224.
- Chen, K.H., Chen, S.J.G., Lin, L., Changchien, S.W., 1998. An integrated graphical user interface (GUI) for concurrent engineering design of mechanical parts. *Computer Integrated Manufacturing Systems* 11, 91-112.
- Chen, M.-S., Lin, C.-C., Tai, Y.-Y., Lin, M.-C., 2011. A Grey Relation Approach to the Integrated Process of QFD and QE. *Concurrent Engineering-Research and Applications* 19, 35-53.
- Chen, W., Hoyle, C., Wassenaar, H.J., 2012. *Decision-based design: Integrating consumer preferences into engineering design*. Springer Science & Business Media.
- Cheng, C.C.J., Huizingh, E.K.R.E., 2014. When Is Open Innovation Beneficial? The Role of Strategic Orientation. *Journal of Product Innovation Management* 31, 1235-1253.
- Chesbrough, H., 2010. *Business Model Innovation: Opportunities and Barriers*. *Long Range Planning* 43, 354–363.

- Chou, J.-R., 2014. An ARIZ-based life cycle engineering model for eco-design. *Journal of Cleaner Production* 66, 210-223.
- Cocca, S., Ganz, W., 2015. Requirements for developing green services. *Service Industries Journal* 35, 179-196.
- Counsell, J., Puybaraud, M.-C., 2006. Visible display of automated observation of collaborative workspaces, *International Conference on Cooperative Design, Visualization and Engineering*. Springer, pp. 192-199.
- Cross, N., 1989. *Engineering Designs Methods*. John Wiley & Sons, Chichester.
- Crowder, R., Fowler, D., Reul, Q., Sleeman, D., Shadbolt, N., Wills, G., 2012. An information system to support the engineering designer. *Journal of Intelligent Manufacturing* 23, 1545-1558.
- De Benedetti, B., Toso, D., Baldo, G.L., Rollino, S., 2010. EcoAudit: a Renewed Simplified Procedure to Facilitate the Environmentally Informed Material Choice Orienting the Further Life Cycle Analysis for Ecodesigners. *Materials Transactions* 51, 832-837.
- Dekkers, R., 2000. Decision models for outsourcing and core competencies in manufacturing. *International Journal of Production Research* 38, 4085-4096.
- Desai, A., Lindahl, M., Widgren, M., 2015. Actors and System Maps – A Methodology for Developing Product/Service Systems, in: Matsumoto, M., Masui, K., Fukushima, S., Kondoh, S. (Eds.), *Sustainability Through Innovation in Product Life Cycle Design*. Springer Verlag, Singapore, p. 1046.
- Design, N.R.C.C.o.T.F.f.D.M.i.E., 2001. *Theoretical foundations for decision making in engineering design*. National Academy Press.
- Di Bucchianico, G., Gregori, M., Rossi, E., 2012. Designing from activities. The "ability/difficulty table", a useful tool to detect the "limit users" in the Design for All Approach. *Work-a Journal of Prevention Assessment & Rehabilitation* 41, 1362-1367.
- Dieter, G.E., Schmidt, L.C., 2013. *Engineering design*. McGraw-Hill New York.
- Dixon, J.R., Poli, C., 1995. *Engineering Design And Design For Manufacturing*. Field Stone Publishers.
- Durugbo, C., 2013a. Competitive product-service systems: lessons from a multicase study. *International Journal of Production Research* 51, 5671-5682.
- Durugbo, C., 2013b. Integrated product-service analysis using SysML requirement diagrams. *Systems Engineering* 16, 111-123.
- Eisenhardt, K.M., Graebner, M.E., 2007. Theory building from cases: Opportunities and challenges. *Academy of management journal* 50, 25-32.
- Erkoyuncu, J.A., Roy, R., Shehab, E., Kutsch, E., 2014. An innovative uncertainty management framework to support contracting for product-service availability. *Journal of Service Management* 25, 603-638.
- Garetti, M., Rosa, P., Terzi, S., 2012. Life Cycle Simulation for the design of Product-Service Systems. *Computers in Industry* 63, 361-369.
- Gatenby, D.A., Lee, P.M., Howard, R.E., Hushyar, K., Layendecker, R., Wesner, J., 1994. CONCURRENT ENGINEERING - AN ENABLER FOR FAST, HIGH-QUALITY PRODUCT REALIZATION. *At&T Technical Journal* 73, 34-47.
- Geelen, D., Reinders, A., Keyson, D., 2013. Empowering the end-user in smart grids: Recommendations for the design of products and services. *Energy Policy* 61, 151-161.
- Georgiadis, D.R., Mazzuchi, T.A., Sarkani, S., 2013. Using multi criteria decision making in analysis of alternatives for selection of enabling technology. *Systems Engineering* 16, 287-303.
- Gero, J.S., 1990. Design prototypes: a knowledge representation schema for design. *AI magazine* 11, 26.
- Gero, J.S., Kannengiesser, U., 2004. The situated function-behaviour-structure framework. *Design studies* 25, 373-391.
- Ghahramani, B., Houshyar, A., 1996. Benchmarking the application of quality function deployment in rapid prototyping. *Journal of Materials Processing Technology* 61, 201-206.
- Ghahramani, B., Wang, Z., 1998. Analyzing manufacturing process information. *Journal of Materials Processing Technology* 76, 270-275.
- Goffin, K., 2000. Design for supportability: Essential component of new product development. *Research-Technology Management* 43, 40-47.
- Goh, Y.M., Giess, M., McMahon, C., 2009. Facilitating design learning through faceted classification of in-service information. *Advanced Engineering Informatics* 23, 497-511.
- Gu, P., Sosale, S., 1999. Product modularization for life cycle engineering. *Robotics and Computer-Integrated Manufacturing* 15, 387-401.
- Hansen, C.T., Andreasen, M.M., 2003. A proposal for an enhanced design concept understanding, in: Sellgren, U. (Ed.). *KTH, Department of Machine Design, Stockholm*.

- Hazelrigg, G.A., 1998. A framework for decision-based engineering design. *Journal of mechanical design* 120, 653-658.
- Heisig, P., Caldwell, N.H.M., Clarkson, P.J., 2014. Core information categories for engineering design - contrasting empirical studies with a review of integrated models. *Journal of Engineering Design* 25, 88-124.
- Hippel von, E., 2005. *Democratizing Innovation*. MIT Sloan School of Management.
- Hvam, L., Haug, A., Mortensen, N.H., Thuesen, C., 2013. OBSERVED BENEFITS FROM PRODUCT CONFIGURATION SYSTEMS. *International Journal of Industrial Engineering-Theory Applications and Practice* 20, 329-338.
- Igba, J., Alemzadeh, K., Gibbons, P.M., Henningsen, K., 2015. A framework for optimising product performance through feedback and reuse of in-service experience. *Robotics and Computer-Integrated Manufacturing* 36, 2-12.
- Isaksson, O., Larsson, T.C., Rönnbäck, A.Ö., 2009. Development of product-service systems: challenges and opportunities for the manufacturing firm. *Journal of Engineering Design* 20, 329-348.
- Jagtap, S., Johnson, A., 2011. In-service information required by engineering designers. *Research in Engineering Design* 22, 207-221.
- Kindström, D., Kowalkowski, C., 2014. Service innovation in product-centric firms: A multidimensional business model perspective. *Journal of Business & Industrial Marketing* Vol. 29.
- Komoto, H., Tomiyama, T., 2008. Integration of a service CAD and a life cycle simulator. *Cirp Annals-Manufacturing Technology* 57, 9-12.
- Kowalkowski, C., Kindström, D., Brehmer, P.-O., 2009. Managing industrial service offerings: requirements on content and processes. *International Journal of Services Technology and Management* Vol. 11, pp 42-63.
- Lee, J.-K., Kim, H.S., Kuk, S.H., Park, S.-W., 2006. Development of an e-engineering framework based on service-oriented architectures, in: Luo, Y. (Ed.), *Cooperative Design, Visualization, and Engineering*, Proceedings, pp. 251-258.
- Lindahl, M., 2005. *Engineering Designers' Requirements on Design for Environment Methods and Tools*, Industrial Engineering and Management. The Royal Institute of Technology, Stockholm.
- Lindahl, M., Sundin, E., 2012. Product Design Considerations for Improved Integrated Product/Service Offerings, *Handbook of Sustainable Engineering*. Springer.
- Lindahl, M., Sundin, E., Sakao, T., 2014. Environmental and economic benefits of Integrated Product Service Offerings quantified with real business cases. *Journal of Cleaner Production* 64, 288-296.
- Luttropp, C., Lagerstedt, J., 2006. EcoDesign and The Ten Golden Rules: generic advice for merging environmental aspects into product development. *Journal of Cleaner Production* 14, 1396-1408.
- Manley, J.H., 1996. Enterprise information system modeling for continuous improvement. *Computers & Industrial Engineering* 31, 273-276.
- Maussang, N., Zwolinski, P., Brissaud, D., 2009. Product-service system design methodology: from the PSS architecture design to the products specifications. *Journal of Engineering Design* 20, 349-366.
- Meier, H., Massberg, W., 2004. Life cycle-based service design for innovative business models. *CIRP Annals-Manufacturing Technology* 53, 393-396.
- Meier, H., Roy, R., Seliger, G., 2010a. Industrial Product-Service Systems-IPS2. *Cirp Annals-Manufacturing Technology* 59, 607-627.
- Meier, H., Roy, R., Seliger, G., 2010b. Industrial Product-Service Systems – IPS<sup>2</sup>. *CIRP Annals Manufacturing Technology* 59, 607-627.
- Ming, X.G., Yan, J.Q., Wang, X.H., Li, S.N., Lu, W.F., Peng, Q.J., Ma, Y., 2008. Collaborative process planning and manufacturing in product lifecycle management. *Computers in Industry* 59, 154-166.
- Molina, A., Aca, J., Wright, P., 2005. Global collaborative engineering environment for integrated product development. *International Journal of Computer Integrated Manufacturing* 18, 635-651.
- Mont, O.K., 2002. Clarifying the concept of product-service system. *Journal of Cleaner Production* 10, 237-245.
- Morelli, N., 2002. Designing product/service systems: A methodological exploration1. *Design issues* 18, 3-17.
- Moreno, D.P., Hernandez, A.A., Yang, M.C., Otto, K.N., Hoelttae-Otto, K., Linsey, J.S., Wood, K.L., Linden, A., 2014. Fundamental studies in Design-by-Analogy: A focus on domain-knowledge experts and applications to transactional design problems. *Design Studies* 35, 232-272.
- Neugebauer, L., Universitet, D.T., Mouggaard, K., Andersen, J.B., McAloone, T., Bey, N., Hsuan, J., Ahm, T., Engineering, T.U.o.D.o.M., 2012. *PSS Case Book: A Workbook in the PROTEUS Series*. Technical University of Denmark.
- Nixon, B., 1999. Evaluating design performance. *International Journal of Technology Management* 17, 814-829.
- Pahl, G., Beitz, W., Feldhusen, J., Grote, K.H., Wallace, K., Blessing, L.T.M., 2006. *Engineering Design: A Systematic Approach*, 3rd edition ed. Springer, London.

- Roozenburg, N.F.M., Eekels, J., 1995. *Product Design: Fundamentals and Methods*. John Wiley & Sons, Ltd., West Sussex, UK.
- Sadek, T., Welp, E.G., 2009. A model based approach for conceptual development of Industrial Product-Service Systems, DS 58-4: Proceedings of ICED 09, the 17th International Conference on Engineering Design, pp. 155-166.
- Sakao, T., Berggren, C., Björkman, M., Kowalkowski, C., Lindahl, M. Olhager, J., Sandin, J., Sundin, E., Tang, O., Thollander, P., Witell, L. , 2011. Research on Services in the Manufacturing Industry based on a Holistic Viewpoint and Interdisciplinary Approach. Functional Thinking for Value Creation, in: Hesselbach, J., C., H. (Eds.), Proceedings of the 3rd CIRP International Conference on IPS<sup>2</sup>. Springer, Heidelberg, pp. 27-32, ISBN: 978-973-642-19688-19681.
- Sakao, T., Lindahl, M., 2012. A value based evaluation method for Product/Service System using design information. *CIRP Annals - Manufacturing Technology* 61, 51-54.
- Sakao, T., Lindahl, M., 2015. A method to improve integrated product service offerings based on life cycle costing. *CIRP Annals - Manufacturing Technology* 64, 33-36.
- Sakao, T., Shimomura, Y., 2007. Service Engineering: a novel engineering discipline for producers to increase value combining service and product. *Journal of Cleaner Production* 15, 590-604.
- Sampson, S.E., Spring, M., 2012. Customer Roles in Service Supply Chains and Opportunities for Innovation. *Journal of Supply Chain Management* 48, 30-50.
- Schott, H., Gruener, C., Buettner, K., Dannheim, F., 1997. Design for environment - computer based product and process development, in: Krause, F.L., Seliger, G. (Eds.). London, Chapman & Hall, pp. 174-187.
- Selviaridis, K., Spring, M., Araujo, L., 2013. Provider involvement in business service definition: A typology. *Industrial Marketing Management* 42, 1398-1410.
- Shah, J.J., Kulkarni, S.V., Vargas-Hernandez, N., 2000. Evaluation of idea generation methods for conceptual design: effectiveness metrics and design of experiments. *Journal of mechanical design* 122, 377-384.
- Shimomura, Y., Kimita, K., Tateyama, T., Akasaka, F., Nemoto, Y., 2013. A method for human resource evaluation to realise high-quality PSSs. *Cirp Annals-Manufacturing Technology* 62, 471-474.
- Shu, Q., Wang, C., 2007. A conceptual framework for product lifecycle modelling. *Enterprise Information Systems* 1, 353-363.
- Sim, S.K., Duffy, A.H., 2003. Towards an ontology of generic engineering design activities. *Research in Engineering Design* 14, 200-223.
- Solesvik, M.Z., 2006. The use of cooperative visualization in the enhancement of corporate planning in small and medium-sized enterprises, *International Conference on Cooperative Design, Visualization and Engineering*. Springer, pp. 49-56.
- Song, W., Ming, X., Han, Y., Wu, Z., 2013. A rough set approach for evaluating vague customer requirement of industrial product-service system. *International Journal of Production Research* 51, 6681-6701.
- Swarnkar, R., Choudhary, A.K., Harding, J.A., Das, B.P., Young, R.I., 2012. A framework for collaboration moderator services to support knowledge based collaboration. *Journal of Intelligent Manufacturing* 23, 2003-2023.
- Tan, A.R., 2010. *Service-oriented Product Development Strategies*, Danmarks Tekniske Universitet. DTU Management. DTU Management Engineering.
- Tidd, J., Bessant, J., Pavitt, K., 2005. *Managing Innovation: Integrating Technological, Market and Organizational Change*. Wiley.
- Tukker, A., 2004. Eight Types of Product-Service System: Eight Ways to Sustainability? *Experiences from Suspronet. Business Strategy and the Environment* Vol. 13, 246-260.
- Tukker, A., Tischner, U., 2006a. *New Business for Old Europe*. Greenleaf Publishing, Sheffield.
- Tukker, A., Tischner, U., 2006b. *New Business for Old Europe. Product Services, Sustainability and Competitiveness*. Greenleaf Publishing Ltd., Sheffield, UK.
- Uflacker, M., Zeier, A., 2011. A semantic network approach to analyzing virtual team interactions in the early stages of conceptual design. *Future Generation Computer Systems-the International Journal of Grid Computing and Esience* 27, 88-99.
- Ullman, D., G., 2002a. *The Mechanical Design Process, Third Edition* ed. McGraw-Hill Higher Education, New York, USA.
- Ullman, D., G., 2002b. *The Mechanical Design Process*. McGraw-Hill Higher Education, New York.
- Ulrich, K., Eppinger, S., 2011a. *Product Design and Development, 5th edition* ed. McGraw-Hill/Irwin.
- Ulrich, K.T., Eppinger, S.D., 2000. *Product Design And Development*. Irwin McGraw-Hill.

- Ulrich, K.T., Eppinger, S.D., 2011b. Product design and development, 5<sup>th</sup> edition ed. McGraw-Hill Education.
- Umeda, Y., Takata, S., Kimura, F., Tomiyama, T., Sutherland, J.W., Kara, S., Herrmann, C., Dufloy, J.R., 2012. Toward integrated product and process life cycle planning-An environmental perspective. *Cirp Annals-Manufacturing Technology* 61, 681-702.
- van der Merwe, C., van Rensburg, A., Schutte, C.S.L., 2015. AN ENGINEERING APPROACH TO AN INTEGRATED VALUE PROPOSITION DESIGN FRAMEWORK. *South African Journal of Industrial Engineering* 26, 59-74.
- Wang, L., Shen, W., Xie, H., Neelamkavil, J., Pardasani, A., 2002. Collaborative conceptual design—state of the art and future trends. *Computer-Aided Design* 34, 981-996.
- Vargo, S.L., Lusch, R.F., 2004. Evolving to a new dominant logic for marketing. *Journal of marketing* 68, 1-17.
- Vasanth, G.V.A., Roy, R., Lelah, A., Brissaud, D., 2012. A review of product–service systems design methodologies. *Journal of Engineering Design* 23, 635-659.
- Watanabe, K., Mikoshiba, S., Tateyama, T., Shimomura, Y., 2012. Service process simulation for integrated service evaluation. *Journal of Intelligent Manufacturing* 23, 1379-1388.
- Vianello, G., Ahmed-Kristensen, S., 2012. A comparative study of changes across the lifecycle of complex products in a variant and a customised industry. *Journal of Engineering Design* 23, 99-117.
- Wong, S.C., Crowder, R.M., Wills, G.B., Shadbolt, N.R., 2008. Knowledge transfer: From maintenance to engine design. *Journal of Computing and Information Science in Engineering* 8.
- Wrisberg, N., de Haes, H.A.U., Triebswetter, U., Eder, P., Clift, R., 2002. Analytical tools for environmental design and management in a systems perspective: the combined use of analytical tools. Springer Science & Business Media.
- Xu, Y., Liu, W., 2006. A collaborative design platform for assembly process planning, International Conference on Cooperative Design, Visualization and Engineering. Springer, pp. 33-40.
- Yin, C.G., Ma, Y.S., 2012. Parametric feature constraint modeling and mapping in product development. *Advanced Engineering Informatics* 26, 539-552.
- Zeng, L., Proctor, R.W., Salvendy, G., 2011. Fostering Creativity in Product and Service Development: Validation in the Domain of Information Technology. *Human Factors* 53, 245-270.

## **Appendix 1 - The method used for searching the relevant literature**

The literature review was carried out with Web of Science (provided by Thomson Reuters previously and by Clarivate Analytics at present) as the database, and the search was conducted on the 18<sup>th</sup> of April 2016 with the following terms used: (PSS or *(product and service)*) and *engineering and (design\* or develop\*) and (lifecycle or eco\* or resource\* or life-cycle or "life cycle" or sustainab\* or environment\*)*. 1,254 papers were hit in total, which were narrowed down by language (English) and by document type (article or review) to 598. These papers were further screened by manually reading, at least, a title and an abstract of each individual paper so that 150 relevant papers were obtained. These 150 papers fell into the literature pool that was analysed in this work.

## Appendix 2 - The questions asked in this review and references useful for the questions

Questions	References
1. Describe the design process of how you develop an offering. a. What are the key-activities? b. Describe the process when working with requirements. c. Describe the process of conceptual design. d. Describe the process for analysis and evaluation.	(Ulrich and Eppinger, 2000) (Ullman, 2002)
e. What actors are involved in the development process?	(Mont, 2002) (Uflacker and Zeier, 2011) (Shimomura et al., 2013) (van der Merwe et al., 2015) (Ming et al., 2008) (Sampson and Spring, 2012) (Yin and Ma, 2012b) (Bouchlaghem et al., 2005) (Yin and Ma, 2012a) (Marras and Hancock, 2014) (Eden et al., 2008)
f. What actors are perceived as the most important?	(Sampson and Spring, 2012) (Geelen et al., 2013)
i. Why are these important?	(Meier et al., 2010) (Selviaridis et al., 2013)
g. How do different actors interact?	(Uflacker and Zeier, 2011)
i. What do they communicate?	(Swarnkar et al., 2012)
ii. How do they communicate?	(Shimomura et al., 2013) (van der Merwe et al., 2015) (Ming et al., 2008) (Sampson and Spring, 2012) (Selviaridis et al., 2013) (Yin and Ma, 2012a) (Marras and Hancock, 2014) (Eden et al., 2008)

<p>2. What types of requirements are considered in the design process?</p> <p>a. From what do the requirements originate?</p>	<p>(Meier et al., 2010) (Vasantha et al., 2012) (Mont, 2002) (Azadi and Saen, 2013) (Brown, 1991) (Chen et al., 2011) (Cocca and Ganz, 2015) (Crowder et al., 2012) (Ghahramani and Houshyar, 1996) (Ghahramani and Wang, 1998) (Goffin, 2000) (Gu and Sosale, 1999) (Isaksson et al., 2009) (Maussang et al., 2009) (van der Merwe et al., 2015) (Vianello and Ahmed-Kristensen, 2012) (Wong et al., 2008) (Luttropp and Lagerstedt, 2006) (Song et al., 2013)</p>
<p>b. What type of information is needed to create the requirement specification?</p> <p>c. How is the information found?</p>	<p>(Ulrich and Eppinger, 2000) (Berkovich et al., 2011) (Wong et al., 2008) (Ashworth et al., 1996) (Crowder et al., 2012) (Durugbo, 2013a) (Ghahramani and Wang, 1998) (Goh et al., 2009) (Heisig et al., 2014) (Hvam et al., 2013) (Igba et al., 2015) (Isaksson et al., 2009) (Jagtap and Johnson, 2011) (Shu and Wang, 2007) (Vianello and Ahmed-Kristensen, 2012) (Wong et al., 2008)</p>
<p>3. Which environmental categories do the requirements belong to?</p>	<p>(Vezzoli and Sciama, 2006) (Cocca and Ganz, 2015) (Durugbo, 2013a) (Luttropp and Lagerstedt, 2006)</p>
<p>4. What types of aspects are considered beside requirements? (Designers capability, production feasibility)</p>	<p>(Ullman, 2002) (Chen et al., 2011) (Cocca and Ganz, 2015) (Gu and Sosale, 1999) (Maussang et al., 2009)</p>

5. How are these prioritized, among each other?	(Berkovich et al., 2014) (Azadi and Saen, 2013) (Brown, 1991) (Chen et al., 2011) (Ghahramani and Houshyar, 1996) (Goffin, 2000) (Song et al., 2013)
6. Which requirements are most difficult to fulfil?	(Berkovich et al., 2014)
7. How are requirements communicated to involved actors?	(Smith and Reinertsen, 1998) (Ashworth et al., 1996) (Crowder et al., 2012) (Goh et al., 2009) (Heisig et al., 2014) (Jagtap and Johnson, 2011) (Ming et al., 2008) (Shu and Wang, 2007) (van der Merwe et al., 2015) (Wong et al., 2008)
8. What methods are used to work with requirements?	(Büyükoçkan and Berkol, 2011) (Ashworth et al., 1996) (Azadi and Saen, 2013) (Brown, 1991) (Chen et al., 2011) (Crowder et al., 2012) (Ghahramani and Houshyar, 1996) (Ghahramani and Wang, 1998) (Goffin, 2000) (Goh et al., 2009) (Gu and Sosale, 1999) (Igba et al., 2015) (Maussang et al., 2009) (Shu and Wang, 2007) (van der Merwe et al., 2015) (Wong et al., 2008) (Song et al., 2013) (Berkovich et al., 2014)
9. How are requirements used in the conceptual design? a. How are the other aspects than the requirements used?	(Wang et al., 2002) (Watanabe et al., 2012) (Shimomura et al., 2013) (van der Merwe et al., 2015) (Ming et al., 2008) (Sampson and Spring, 2012) (Di Bucchianico et al., 2012) (Agost et al., 2006) (Wang et al., 2006) (Geelen et al., 2013) (Zeng et al., 2011) (Molina et al., 2005)

	<p>(Meier et al., 2010)  (Yin and Ma, 2012b)  (Selviaridis et al., 2013)  (Umeda et al., 2012)  (Nivala et al., 2007)</p>
<p>10. How are different actors involved in the conceptual design?  a. When in the conceptual design are they involved?</p>	<p>(Mont, 2002)  (Andreasen et al., 2015)  (Shah et al., 2000)  (Zeng et al., 2011)  (Uflacker and Zeier, 2011)  (van der Merwe et al., 2015)  (Counsell and Puybaraud, 2006)  (Eden et al., 2008)</p>
<p>11. What methods are used during conceptual design?</p>	<p>(Andreasen et al., 2015)  (Shah et al., 2000)  (Zeng et al., 2011)  (Uflacker and Zeier, 2011)  (Gu and Sosale, 1999)  (Swarnkar et al., 2012)  (Watanabe et al., 2012)  (Maussang et al., 2009)  (Buyukozkan et al., 2004)  (van der Merwe et al., 2015)  (Sampson and Spring, 2012)  (Di Bucchianico et al., 2012)  (Solesvik, 2006)  (Agost et al., 2006)  (Xu and Liu, 2006)  (Molina et al., 2006)  (Migilinskas and Ustinovichius, 2006)  (Lindahl et al., 2014)  (Nixon, 1999)  (Moreno et al., 2014)  (Molina et al., 2005)  (Sakao and Shimomura, 2007)  (Umeda et al., 2012)  (Bouchlaghem et al., 2005)</p>
<p>12. How are requirements used to evaluate concepts?  a. How are other aspects than requirements used?  b. What environmental issues are considered?</p>	<p>(Durugbo, 2013b)  (Schmidt et al., 2015)  (Buxel et al., 2015)  (Song et al., 2014)  (Igba et al., 2015)  (Maussang et al., 2009)  (Pigosso et al., 2016)  (Åkermark, 1999)  (Ritzén, 1996)</p>

<p>c. How important are economic versus environmental aspects?</p>	<p>(Sakao and Lindahl, 2015) (Frutos et al., 2004) (Georgiadis et al., 2013) (De Benedetti et al., 2010) (Chou, 2014) (Lindahl et al., 2014) (Cheaitou and Khan, 2015) (Beskow, 2000) (Zika-Viktorsson, 2002)</p>
<p>13. How are uncertainties addressed?</p>	<p>(Erkoyuncu et al., 2013) (Garetti et al., 2012) (Sakao et al., 2013) (Fallah et al., 2015) (Erkoyuncu et al., 2014) (Geng et al., 2011) (Hansson, 1996) (Chen et al., 2012) (Mintzberg et al., 1976) (Langley et al., 1995)</p>
<p>14. What methods are used during analysis and evaluation?</p>	<p>(Cavalieri and Pezzotta, 2012) (Krishnan and Ulrich, 2001) (Georgiadis et al., 2013) (Bertoni et al., 2015) (NRC, 2001) National Research Council (NRC, 2002) National Research Council (Hatamura, 2006)</p>
<p>15. Out of the earlier mentioned methods, describe the purpose of methods used.</p> <p>a. Who uses them?</p> <p>b. What input is required?</p> <p>i. Are the required data qualitative or quantitative?</p> <p>ii. How do you address subjectivity issues?</p> <p>c. What output do the methods deliver?</p> <p>d. How do you perceive the quality of the outcome of the method? (trust, etc.)</p>	<p>(Pigosso et al., 2010) (Morelli, 2002) (Alonso-Rasgado et al., 2004) (Shu and Wang, 2007) (Sandberg et al., 2005) (Ulrich and Eppinger, 2000) (Unger and Eppinger, 2011) (Dieter and Schmidt, 2013)</p>
<p>16. How are the methods perceived to work with?</p>	<p>(Matschewsky et al., 2015) (Chen et al., 1998) (Gatenby et al., 1994) (Heisig et al., 2014) (Manley, 1996) (Reich, 2010)</p>
<p>17. What type of training is offered to the users of the methods?</p>	<p>(Sakao and Shimomura, 2007) (Tate et al., 2010) (Unger and Eppinger, 2011)</p>

<p>18. What are the biggest challenges with current methods?</p>	<p>(Cavalieri and Pezzotta, 2012) (Vasantha et al., 2012) (Matschewsky et al., 2015) (Ming et al., 2008) (Neto et al., 2015) (Courage and Baxter, 2005) (Chakrabarti and Lindemann, 2016)</p>
<p>19. What indicators are used to measure performance in the development process?</p>	<p>(Neely et al., 1995) (Nixon, 1999) (Bieda, 1992) (Watanabe et al., 2012) (Brad, 2009)</p>

## Appendix 3 – Definitions

This report adopts definitions below. In case a specific reference is not shown, a suitable definition was made by the authors based on several references.

- **Actor** - An individual, group or organization that plays a specified role in interacting with a solution. (Based on: *BABOK, V3, A Guide to the business analysis body of knowledge, 2015, pp.441*)
- **Design process** - A set of activities to achieve an offering to be realized
- **Method** - A predefined description that support achieving a specific goal.
- **Effective** - Successful in solving one or more needs of targeted and relevant actors.
- **Efficient** - Maximum ratio of an output to the corresponding input. (ISO/TR 11065:1992)
- **Offering** - A suggestion of a solution.
- **Product** - A physical entity with value in a defined context. (including software)
- **Resource** - Any asset (human, physical, information or intangible), facilities, equipment, materials, products or waste that has potential value and can be used (ISO 28002:2011).
- **Service** - An activity with value in a defined context.
- **Solution** - A specific way of satisfying one or more needs with product and/or service in a defined context. (Based on: *Beyond Requirements: Analysis with an Agile Mindset, AvKent J. McDonald, 2015*)
- **Tool** - An instrument that enables performing a certain task. (Based on: *CIRP Encyclopedia of Production Engineering, 2014, pp 386-388*)
- **Uncertainty** - A state of deficiency of information related to a future event.