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Early stages of *designing* resource-efficient
offerings
An initial view of their analysis and evaluation

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Abstract

The increasing use of natural resources and the pollution it causes calls for new ways of addressing customer needs. Additionally, a more uncertain and complex world also presents new challenges. In this thesis, these new challenges are tackled through inter and transdisciplinary research, which require more interaction across disciplines to tackle complex phenomena.

The manner in which companies address customer needs starts from the *designing* (a multiple-stakeholder perspective) of offerings where companies rely on different types of support (guidelines, standards, methods and tools). In this thesis, these offerings, include products, services, systems, and solutions. This plays an important role in the use of natural resources and its impact on the environment. In this Licentiate, I present results to show initial cues on how to design resource-efficient offerings, and more specifically their analysis and evaluation in the early stages of the design process. This type of offerings is suggested to be crucial for the circular economy, which can be understood as a paradigm shift towards sustainability. In this paradigm shift, designing is carried out by taking into account reuse, remanufacture and recycling of products as strategies by multiple stakeholders and companies. Other strategies include providing services, a function or a solution through dematerialization and transmaterialization.

The methods used in this research are narrative and systematic literature reviews, thematic analysis and a case study. The results show a lack of interdisciplinary research in the academic literature in subjects relevant to the design of resource-efficient offerings. The results also show a need to clarify what transdisciplinary research entails. Moreover, current practice shows that support used by companies needs to consider several factors for it to be useful, for example, the vision of the company, participation of potential users of the support and everyday operations, among other characteristics. Finally, more practical support coming from academia is necessary to improve its use in industry.

Keywords: Design, analysis, evaluation, ecodesign, product/service systems, resource-efficient offerings, circular economy, interdisciplinary research, transdisciplinary research.

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Appendix III Paper III: Brambila-Macias, S. A., Dahllöf, L., Eriksson, K., Sakao, T. (2018) Development of an environmental evaluation tool in the transport sector and its impact on decision-making in the early stages of design. In *Life Cycle Management Conference 2018* (accepted).

Appendix IV Paper IV: Brambila-Macias, S.A., Sakao, T. & Kowalkowski, C. (n.a.) Bridging the Gap between Engineering Design and Marketing: Insights for Research and Practice of Product/Service System Design Submitted to a design journal (in revision after the first review).

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Preface

Audience: This research has as its primary audience researchers involved in the study of design and development of products, services and systems. It mainly focuses on introducing environmental aspects in the design process. Practitioners can also benefit from this research as a source of the state of the art in support for environmental sustainability in engineering design. The wider audience, especially students in product development and environmental management, can benefit by looking at how manufacturing companies and academia are working together to manage environmental challenges and the skills that they would need to acquire going forward in their careers.

Title: The title highlights the different components of what this research is about. Designing (the process, the verb) is differentiated from design (the event, the noun) to emphasize the social process of *designing* with its multiple stakeholders, multiple objectives and multiple iterations, and which goes beyond a company's boundaries: one in which not only designers per se but also project managers, marketing professionals, purchasers, quality managers, suppliers and customers, among other actors, are involved. Moreover, the early stages of designing can include planning, project proposals, conceptual design and feasibility studies, among other activities, with the objective of determining the allocation of resources for the consecutive stages in the design process. This broad perspective is based on what has been observed in industry, relevant literature and what resource efficiency entails. With regard to resource efficiency, this encompasses a wide range of strategies that look for less use of natural resources while minimizing the impact to the environment through the paradigm change of the circular economy. Offerings include products, services, systems and solutions for customers.

My background: Finally, in this preface I would also like to provide my academic background for a better understanding of my own worldview and possible unconscious biases in this research. Education has shaped my mind; my initial studies in industrial and systems engineering taught me to look at processes through mapping necessary inputs, efficient transformations and useful outputs. Complementary to this, my advanced studies in international business, supply chain management, energy and environmental engineering have provided me with a broader view of different disciplines and a holistic approach when addressing problems. To address these many disciplines and fields of study I constantly make an effort to seek structure and clarity that can help me navigate and categorize different themes, a big picture approach. It is my hope that this effort for structure and clarity in what could be considered *messy* or *overly broad* is communicated throughout the different chapters, and that attention to detail or specialization is not entirely sacrificed.

Appended papers and contribution

In order of publication

Paper I

Brambila-Macias, S. A., Sakao, T., & Kowalkowski, C. (2016). Interdisciplinary Insights Found for Product/Service System Design. In *Proceedings of the DESIGN 2016 14th International Design Conference* (published). In this conference paper, I read and analyzed the literature in a systematic manner to look at how the disciplines of engineering design and marketing communicate. I was responsible for most of the writing as well as tables and figures.

Paper II

Sakao, T., & Brambila-Macias, S. A. (2018). Do we share an understanding of transdisciplinarity in environmental sustainability research? *Journal of Cleaner Production*, 170, 1399-1403 (published). In this paper, I shared responsibility with my main supervisor in writing and producing the different tables and figures. Doi 10.1016/j.jclepro.2017.09.226

Paper III

Brambila-Macias, S. A., Dahllöf, L., Eriksson, K., Sakao, T. (2018) Development of an environmental evaluation tool in the transport sector and its impact on decision-making in the early stages of design. In *Life Cycle Management Conference 2017* (accepted for post-conference proceedings 2018). In this conference paper, I was responsible for most of the writing (co-wrote the case study) as well as tables and figures.

Paper IV

Brambila-Macias, S.A., Sakao, T. & Kowalkowski, C. (n.a.) Bridging the Gap between Engineering Design and Marketing: Insights for Research and Practice of Product/Service System Design. Submitted to a design journal (in revision after the first review). This paper is an extension of Paper I. It provides future research directions for PSS. I carried out the three stages of the method proposed in this paper which included the analysis of the literature in a systematic manner, thematic analysis and the proposed research agenda.

Concept definitions

This section presents the definitions of concepts and their understanding in this research.

1. **Analysis** entails problem-solving tools and skills like mathematical equations, modeling and simulation. It starts early in design but increases in complexity as more information becomes available and the project is allocated resources (author's own definition).
2. **Circular economy** is restorative and regenerative by design, and which aims to keep products, components and materials at their highest utility and value at all times, distinguishing between technical and biological cycles (ISO 20400:2017). In this thesis, it is understood as a paradigm shift from a linear to a circular economy through resource-efficient offerings based on reuse, recycle, remanufacture, dematerialization and transmaterialization.
3. **Complexity** is the state of having many parts and being difficult to understand or find an answer to (Cambridge Dictionary, n.d.).
4. **Conceptual design** is a part of the product development process, which includes the preparation of design specifications and design proposals for a product (ISO 11442:2006).
5. **Conceptual stage is where** alternative outline proposals are evaluated and a preferred solution produced sufficiently to obtain client, user and statutory approval, and then developed into a design solution fully integrated with constructional, structural and service requirements (ISO 6707-2:2017). In this thesis, the term "early stages of designing" is preferred as companies may have a different understanding in practice (see definitions below).
6. **Design and development** is a set of processes that transforms requirements into specified characteristics or into the specification of a product, process or system (ISO/TR 14062:2002).
In this thesis:
 - a. **Designing** (the process, the verb) is differentiated from design (the event, the noun) to emphasize the social process of designing with its multiple stakeholders, multiple objectives and multiple iterations, which goes beyond a company's boundaries (author's own understanding).
 - b. **Early stages of designing** can include planning, project proposals, conceptual design and feasibility studies, among other activities, with the objective of determining the allocation of resources for the consecutive stages in the design process (author's own understanding).

7. **Ecodesign** is integration of environmental aspects into product design and development, with the aim of reducing adverse environmental impacts throughout a product's life cycle (ISO 14006:2011).
8. **Evaluation** starts early in design, but with little information. Allocation of resources begins but uncertainty in the final outcome is high. It requires knowledge and experience rather than mathematical equations to ensure an effective outcome (author's own definition).
9. **Interdisciplinary research** can be described as occurring when researchers from two or more disciplines integrate information, data, tools, perspectives, concepts, and/or theories to solve problems whose solutions are beyond disciplinary boundaries (Sakao & Brambila-Macias, 2018).
10. **Knowledge** are facts, information, and skills acquired through experience or education; the theoretical or practical understanding of a subject (Oxford Dictionary, n.d.)
11. **Offering** can be products, services, systems, solutions (author's own definition).
12. **Product Service System** is a marketable set of products and services, jointly capable of fulfilling a client's need (Goedkoop, van Halen, te Riele, & Rommens, 1999).
13. **Resource efficiency means** using the earth's limited resources in a sustainable manner while minimizing impacts on the environment. It allows us to create more with less and to deliver greater value with less input (European Commission, 2017). In this thesis, the implementation of resource-efficient offerings will be based on different strategies such as reuse, recycling, remanufacturing, dematerialization and transmaterialization.
14. **Sustainability** is a state of the global system, including environmental, social and economic aspects, in which the needs of the present are met without compromising the ability of future generations to meet their own needs (ISO/Guide 82:2014). In this thesis, it is understood as a vision of how humans should live.
15. **Transdisciplinary research** is research that transcends disciplines by employing a systemic view (Transdisciplinary 1) or comprehensive frameworks (Transdisciplinary 2) (Sakao & Brambila-Macias, 2018).
16. **Uncertainty** is a situation in which something is not known, or something that is not known or certain (Cambridge Dictionary, n.d.).

1. Introduction

This chapter introduces the context of this research through citing historical milestones in the efforts made so far to minimize human impact on the environment. It also provides some definitions of concepts relevant for this research, namely, *sustainable development*, *sustainability*, *decoupling*, *the circular economy*, and *resource efficiency*. In addition to highlighting Sweden's commitment to sustainability, this section presents the research relevance, problems identified, scope, objectives, research questions and limitations.

1.1 From end-of-pipe technologies to a new economic paradigm

The impact of human activities on the environment has increased in recent years. *The Great Acceleration* since the early 1950s gave rise to the rapid development of technologies, exponential population growth and high demand for materials and energy (Steffen, Broadgate, Deutsch, Gaffney, & Ludwig, 2015). The *Anthropocene* is increasingly the name given to our current geological epoch, one in which humans are having an unprecedented impact on the environment (Steffen, Grinevald, Crutzen, & McNeill, 2011). This epoch is increasingly complex, highly interconnected (Steffen, Persson, et al., 2011), and one which presents *ill-structured* or *wicked problems* that rather than being solved are managed (Lönngren & Svanström, 2016). Literature suggests that environmental pollution caused by human activities attracted little international attention until the 1960s and early 1970s (Du Pisani, 2006; Serrat, 2012). Seminal publications such as Rachel Carson's *Silent Spring* in 1962, Garrett Hardin's article *Tragedy of the Commons* in 1968 and *Limits to growth* by the Club of Rome in 1972 first highlighted environmental issues (Serrat, 2012). Evidence showed that the damage of pesticides to the environment and worsening of living conditions due to population growth and limitless resource consumption needed urgent attention.

One of the early international efforts to address these issues was at The United Nation's Stockholm Conference on Human Environment in 1972. This conference resulted in the creation of the United Nations Environment Programme (UNEP) as well as the Environmental Directorate at the Organization of Economic Cooperation and Development (OECD), which were among several global institutions that started to address environmental problems (Ayres, 2008). During this time, one of the most common approaches used to mitigate human impact on the environment was that of pollution control through *end-of-pipe technologies* (Barrow, 2005). This technology had a more downstream approach, where the effort was on minimizing pollution created by human activities. This approach has been described as limited in its success (Winkler, 2011).

Barrow (2005) suggests that it was not until the mid-1980s and 1990s that cleaner production and environmental management systems first appeared addressing a more holistic approach to environmental impacts. Newer strategies aimed at preventing pollution rather than reacting to it emerged during this period. The *precautionary principle*, preventive actions and the *polluter pays principle* were legislative actions during this period (Hundal, 2001). Although these approaches had more success as compared to end-of-pipe technologies, more radical approaches were later advocated by the UNEP (Manzini & Vezzoli, 2002). However, this new and more radical approach requires a change of economic paradigm (Bonviu, 2014). This change of paradigm could be described with the concept of the *circular economy* (CE), which can be defined as follows:

“A regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling” pp. 759. (Geissdoerfer, Savaget, Bocken, & Hultink, 2017). The following figure provides a view of how the environmental approach has changed over time.

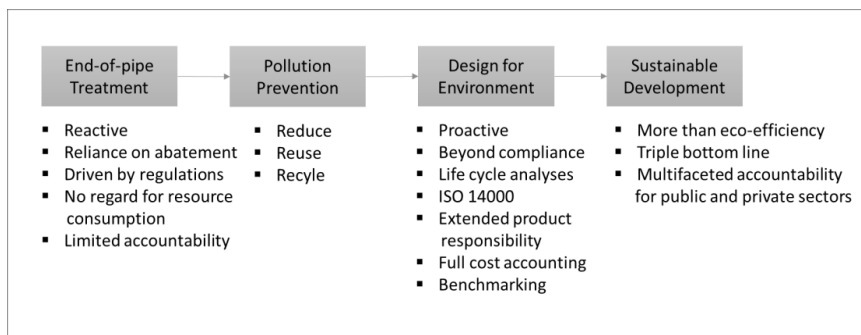


Figure 1. Evolution of environmental approaches (adapted from Mihelcic et al., 2003)

CE is differentiated from the *linear economy*, where increasing production requires more resources from nature and produces unlimited waste (Bonviu, 2014). CE is not a unique approach; its foundations are found in the *performance economy*, *industrial ecology* and the *blue economy*, among others, which have inspired and contributed to its development (Gallaud & Laperche, 2016). The main difference with CE and previous contributions has been greater support from policymakers (Murray, Skene, & Haynes, 2017), NGOs and consultancy companies. For example, CE is part of China's national policy for sustainable development (Geng, Fu, Sarkis, & Xue, 2012), The Ellen MacArthur Foundation and management consultancy McKinsey & Company have provided a framework for the circular economy (MacArthur, 2013), and management consultancy Accenture has also made available publications related to transforming waste into valuable resources (Lacy & Rutqvist, 2015). In Europe, several initiatives for CE have been put forward by the European Commission (European Commission, 2015), and The Swedish Foundation for Strategic Environmental Research (Mistra) has increasingly funded CE projects (Mistra, 2015)

Additionally, it is important to mention Sweden's long history in the conservation of the environment. The country's commitment to nature reflects societal values and those of Swedish organizations when addressing the design process. For instance, already in 1909 the Swedish Parliament passed a law to protect the national parks for tourism and recreation (Angelstam et al., 2011). Moreover, Sweden's initiative for the UN Conference in 1972 as well as the 1979 agreement on long-range transboundary air pollution (Miles, 1996) are some examples of its commitment. Along with Denmark, Finland, Island and Norway (the Nordic countries), Sweden has been influential in the EU's environmental policy (Tunkrova, 2008). In more recent years, other relevant efforts include *The Natural Step* in 1989 (Bradbury & Clair, 1999), *Miljömålen* or environmental objectives in 1991 (Miljömål, 2017), and the *Kretslopp för Hållbar Utveckling* project in 1995 (Johansson, 1995), which can be translated as *Circularity for Sustainable Development*. Sweden's prioritization of the natural environment can also be seen in the latest listing of nations achieving the Sustainable Development Goals (SDGs). *The 2030 Agenda for Sustainable Development* places Sweden in the 1st position, having achieved on average 84.5% of the targets for 2030. Sweden is followed by Denmark, Norway and Finland (Willige, 2017).

With regard to *resource efficiency*, this can be defined as “using the Earth's limited resources in a sustainable manner while minimising impacts on the environment. It allows us to create more with less and to deliver greater value with less input” (European Commission, 2017). The difference between previous concepts (CE, decoupling and sustainability) and resource efficiency is that the latter looks at improving efficiency in terms of inputs and outputs of systems and creating value. This streamlining of inputs and outputs as well as value creation will depend on the different resource-efficient strategies available. These will be reviewed in Chapter 2.

1.2 Relevance of this research

UNEP's (2012) report on 21 issues for the 21st century shows a range of challenges, from climate change to food security to biodiversity, and how these could affect our future. Among these issues is how to deal with waste and scarce resources (in the report an emphasis is on e-waste). UNEP warns that if current manufacturing trends remain unchecked they will accelerate resource depletion and increase waste, which in turn will result in public health risks and higher competition for key minerals. As options to countermeasure these challenges (resource depletion and waste), UNEP suggests a new way of thinking to support a transition to more sustainable practices. It recommends that manufacturers shift from planned obsolescence to planned capacity for evolution, allowing upgrade and reuse in contrast to the constant replacement of goods. UNEP also recommends a life cycle perspective while adjusting the design of products for easier retrieval of valuable materials.

Furthermore, it has been suggested that research in design, engineering education and practice will also need to change. For example, Rosen and Kishawy (2012) suggest that numerous improvements are needed in design for sustainability, and that many experts in the field are calling for more advanced methodologies. Similarly, De los Rios and Charnley (2017) argue that the standard approach of design and engineering is being challenged, and that in the CE there is a need for new skills that can support system transformations. Finally, Bawden and Allenby (2017) warn of the challenges ahead for sustainability and call for reflective action to change our world view, or *Weltanschauung*. In addition, design (as a verb or noun) has been recognized as a central activity in engineering (Dym & Brown, 2012), and the design process as the root of engineering solutions from problem definition to collection of relevant information, development of alternatives, analysis, evaluation, plan of action, and communication of results, among others (National Society of Professional Engineers, 2013). The conceptual design stage has been suggested to be the most important in the engineering design process, and is considered "the phase that makes the greatest demands on the designer, and where there is the most scope for striking improvements. It is the phase where engineering science, practical knowledge, production methods, and commercial aspects need to be brought together, and where the most important decisions are taken" pp. 3. (French, 1999). What is more, in the past, engineering design has been seen as a major source of competitive advantage for companies (Dym, Agogino, Eris, Frey, & Leifer, 2005) and even for nations (National Research Council, 1991).

Finally, the importance of manufacturing cannot be understated. Taylorism, Toyotism and in Sweden the Uddevalla¹ experience point at the importance of using routines, methods and tools and their impact on productivity, quality, flexibility and other "ities", as De Weck et al. (2011) call them, since most of these terms end in "ity". This research, therefore, supports this transition to sustainability by aiding manufacturing companies with new knowledge and practices towards a more sustainable future.

¹ Although more related to the design of production systems, the examples of Taylorism and Toyotism are well-known ways of working in production; The Uddevalla experience refers to a production plant from Volvo located in Uddevalla, Sweden which operated between 1989 and 1993. It was heralded as outstanding in its human-centeredness and high quality of work based on theories of holistic human learning. For more information see *Enriching production: Perspectives on Volvo's Uddevalla plant as an alternative to lean production*, Sandberg (1995).

1.3 Research gaps in engineering design research

In the first editorial of the Design Science journal, Papalambros (2015) suggests that design *happens* in a diversity of disciplines and that it crosses disciplinary boundaries. Papalambros (2015) argues that these different disciplines will have their own language, culture and semantics, and that effort is needed to make design accessible to all. Moreover, in the article "My method is better!", Reich (2010) suggests that design practitioners already use some kind of method in their practice and when confronted with a new method, in this case coming from academia, most designers would find it difficult to replace their favorite method. Reich (2010) argues that justifying a new method is rather difficult, since its successful transfer requires "not just throwing a method over the wall" pp. 140. but embedding it into the firms' practices. Reich (2010) also calls for reflective practice, meaning that researchers need to use their own proposed tools when designing methods. In the following sections as well as in the appended papers, these general issues are explored in more detail.

1.4 Scope and objectives

The scope is to carry out transdisciplinary research in the early stages of designing resource-efficient offerings in order to provide support that facilitates analysis and evaluation. This research is carried out in the manufacturing sector in Swedish industry.

The objectives can be described as follows:

1. To identify the current use of support for analysis and evaluation during early stages of designing in industry.
2. To develop useful support for industry to address resource-efficient offerings in the early stages of designing.

With the scope and objectives in place, the research questions address the current or *as-is* state in industry, and based on that what knowledge is needed for the support, the *to-be* state. The first objective is deployed to the first research question focusing on the current practice of analysis and evaluation, to be shown in the next section. The second objective corresponds to the second research question focusing on developing useful support for resource-efficient offerings.

1.5 Research questions

The research questions address relevant gaps in the literature, namely the lack of useful tools coming from academia and the necessary knowledge to address this and current environmental sustainability challenges.

RQ1 How is analysis and evaluation carried out during the early stages of designing resource-efficient offerings in the manufacturing industry? This research question is addressed in Paper II.

RQ2 What knowledge is needed to develop useful support for the early stages of designing resource-efficient offerings in the manufacturing industry? This research question is addressed in Papers I, III and IV.

The table below shows the relation between research questions and the appended papers:

Table 1 Research questions and appended papers (author's own)

Appended papers	RQ1 How is analysis and evaluation carried out during the early stages of designing resource-efficient offerings in the manufacturing industry?	RQ2 What knowledge is needed to develop useful support for the early stages of designing resource-efficient offerings in the manufacturing industry?
Paper I: Brambila-Macias, S. A., Sakao, T., & Kowalkowski, C. (2016). Interdisciplinary Insights Found for Product/Service System Design. In <i>DS 84: Proceedings of the DESIGN 2016 14th International Design Conference</i> (published).		✓
Paper II: Sakao, T., & Brambila-Macias, S. A. (2018). Do we share an understanding of transdisciplinarity in environmental sustainability research? <i>Journal of Cleaner Production</i> , 170, 1399-1403 (published).		✓
Paper III: Brambila-Macias, S. A., Dahllöf, L., Eriksson, K., Sakao, T. (2018) Development of an environmental evaluation tool in the transport sector and its impact on decision-making in the early stages of design. In <i>Life Cycle Management Conference 2018</i> (accepted).	✓	
Paper IV: Brambila-Macias, S.A., Sakao, T. & Kowalkowski, C. (n.a.) Bridging the Gap between Engineering Design and Marketing: Insights for Research and Practice of Product/Service System Design Submitted to a design journal (in revision after the first review).		✓

1.6 Limitations of the research

As with any other research endeavor, this one has some limitations worth mentioning. One of limitations of the research is related the scope of the sustainability studied. This is mainly limited to environmental and economic sustainability. This does not mean that social aspects are less important, but that the scope is limited to studying the aforementioned aspects. Nevertheless, the work of an engineer is not performed in a vacuum and hence the nature of engineering is associated with societal values which impact designing. While this is acknowledged, social sustainability is not directly covered in this research.

Another limitation is that of the papers published or submitted so far. As this is an ongoing research project, more detailed information on the current state of designing resource-efficient offerings in industry will be expanded in future work, as the analysis of interviews and other research methods like design sessions with practitioners is still ongoing.

Furthermore, this research is part of a larger project called REES (Resource-Efficient and Effective Solutions²). Resource efficiency is covered here, while effective solutions will be part of future work. This research is limited for now to efficiency, as the effectiveness of a solution will depend on business models and how a firm captures value. Future research and collaborations with other researchers in the REES project will provide necessary insights on how to support companies in designing effective and resource-efficient solutions.

Finally, designing is also linked to innovation (Ignatius, 2015), and while this is an important subject, the innovative side of designing is implicit in this research, rather than being the subject of study.

1.7 Structure of the thesis

This thesis is comprised of seven chapters which flow in progression but can also stand on their own. The diagram below shows a simple representation of this thesis.

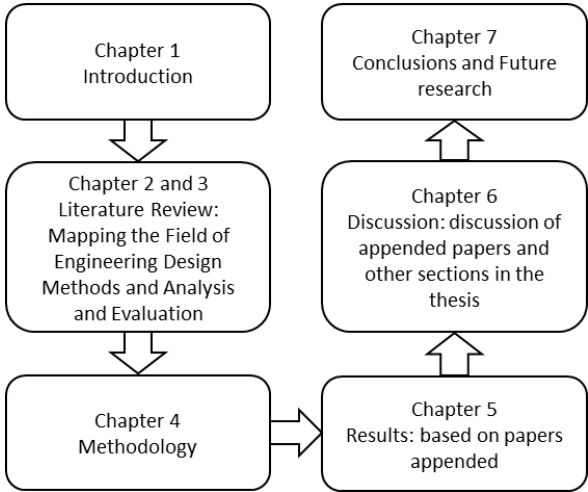


Figure 2 Thesis disposition (author’s own)

² For a more detailed explanation of the research program, please visit the website: <http://mistrarees.se/>

2. Mapping the Field of Engineering Design Methods

This chapter focuses on giving the reader an historic and panoramic view of the main discipline of study, which is *engineering design* and its methods. It then provides more relevant efforts in the literature of design of products, services and systems deemed less detrimental to the environment. These efforts include *ecodesign* and *product/service systems*.

2.1 Engineering design methods

Generally, when addressing design two major paradigms can be discerned (Dorst & Dijkhuis, 1995). On the one hand, Simon’s (1996) *Sciences of the Artificial* (3rd edition) has been heralded as the reason for structured design, a rational and normative view that follows certain steps or a process and in some cases rules when designing (see Suh, 1990). It holds a world view of scientific design as opposed to design as a craft. On the other hand, Schön’s (1983) *The Reflective Practitioner* has usually been described as constructionist (Dorst & Dijkhuis, 1995) and aligning with pragmatism, a view that looks at the field in practice, that is, what professionals actual do. While Schön (1983) acknowledges what the professions have done for the modern society, he also criticizes them for their normative approach to learning and teaching, where students do not face real-world problems until much later in life. Schön (1983) questions how these professions actually contribute to society, giving rise to his ideas of reflection in and on practice. Hubka and Eder (1996) and Meng (2009) view these epistemologies as complementary rather than opposing each other. These world views support the study of what designers actually do (Schön’s view), but also how designers can be taught to design better (Simon’s view). The figure below shows a “map” of the field of engineering design methods. This research has as scope the analysis and evaluation in the early stages of designing effective and resource-efficient offerings

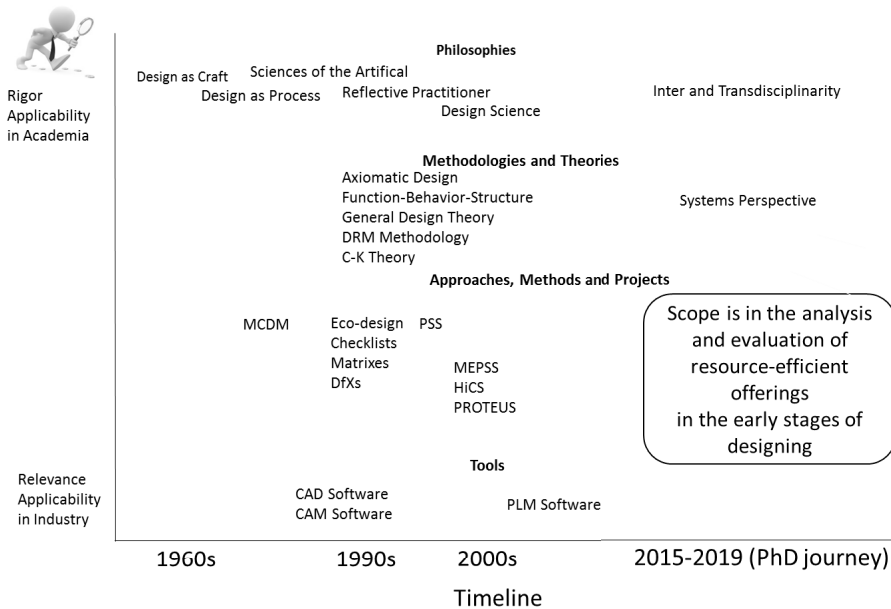


Figure 3 Mapping the field of engineering design methods (author’s own)

It is also important to mention that traditionally, engineering design has been dedicated to products and not services (see, for example, well-known references like Roozenburg and Eekels, 1995 and Pahl and Beitz 2013). However, this approach has changed to include other fields of research. For example, two of the most important publications regarding design of services have been Lynn Shostack’s (1982) *Service Blueprint* on how to design a service and the *Servitization of Businesses* by Vandermerwe and Baumgartner (1988). These design approaches, coupled with the exponential growth of methods on how to make products more sustainable (examples include ecodesign, design for sustainability, and design for serviceability), have allowed companies and customers to think in new ways of fulfilling their needs.

Design (*Designing*) as an approach to tackle environmental problems is the main premise of this research. However, Design can mean different things to different people, and confusion may arise. Questions like what does design mean? How is design carried out? And how can it be studied and taught? have been the focus of extensive research in the past (Bayazit, 2004; Cross, 1993). The field of engineering design methods has gone through different stages since its inception in the early 1960s (Cross, 1993), as explained below.

2.1.1 Early design methods in the 1960s

According to Cross (1993), the event that marked the start of design methods is usually attributed to the *Conference on Design Methods*, held in London in September of 1962. The first books on design methods or methodology appeared in the 1960s. Authors like Hall (1962), Asimow (1962), Alexander (1964) and Archer (1965) all provided the early versions of design methods. They all attempted to clarify or demystify how design was carried out. Bayazit (2004) suggests that creativity methods were developed in the United States in response to the launch of *Sputnik*, the first satellite of the Soviet Union, which pushed the US government to invest in creative methods. It became obvious that designers could no longer only take into account the product as a design task, but had to expand the scope to consider human needs, and a new research field was born: that of design methods.

2.1.2 Period of crisis in the 1970s

This period was marked by the rejection of methods and an identity crisis from their same proponents a decade earlier. There seems to have been a conflict of applicability of methods and hence a lack of trust. Alexander (1964), one of the most prominent proponents of methods, has been quoted to have said in the 1970s “I have dissociated myself from the field...there is so little about design methods that has anything useful”. It seems that this period was marked by the poor usefulness of the methods proposed in academia. Christopher Jones (1970), another early proponent of methods, rejected the attempts made by academics to fix all problems with logical frameworks. Bayazit (2004) suggests that the *first generation* of methods had, in the view of many, turned into an academic subculture.

2.1.3 DfXs and concurrent engineering in the 1980s and mid-1990s

Bayazit (2004) suggests that Horst Rittel, a university professor who coined the term *wicked problems*, welcomed newcomers and saved the field of design methods. A second generation of methods seems to have been born, where user involvement and the identification of their objectives were the main foci. One could argue that it is also during this time that the early DfXs in engineering design first appeared. Design for manufacture and design for assembly served as guidelines in order to design products that could actually be manufactured and assembled. These useful methods are usually attributed to Geoffrey Boothroyd (1994) and his publications on how to design a product with manufacturability in mind. These methods were so successful that a whole range of design for “X” (quality, reliability, logistics, etc.) encountered a whole range of uses. Some other examples of these are Quality Function Deployment or QFD (Akao & Mazur, 2003) and Failure Mode and Effect Analysis or FMEA (Stamatis, 2003), the former for correlating customer needs with quality and the latter for making sure safety and prevention are included in the design or re-design of products.

2.1.4 Environmental concerns in the late 1990s and 2000s

Environmental concerns like pollution, global warming and climate change have slowly shifted the prioritization of profits and efficiencies to a need for methods that also take into account the environment. Ecodesign (Brezet, 1997) and Product-Service Systems (PSS) (Mont 2002) can be considered examples of this period. These will be reviewed in more detail in subsequent sections of this chapter.

2.1.5 Sustainability approach in the 2010s and beyond

According to McAloone and Pigosso (2017), a shift can be observed in today’s society due to globalization, technology and the immediate availability of products and services. This shift has reduced the perceived value of products by their shortened lifetimes and the increasing amount of waste they produce. According to the authors, high-value and high-quality products such as high-end portable computers and premium-priced smartphones, as well as new business models in the form of PSS, are among the answers for product life extension and dematerialization.

2.2 Early stages of designing

Designing can be described as a process consisting of alternations between divergent and convergent processes (Dieter & Schmidt, 2013). The initial phase (in many cases called the conceptual design stage) is considered the most important in terms of costs. It has been estimated that 70 to 80% of product costs are determined during this phase (Ullman, 1992). Engineering design in research and education has traditionally followed a structured approach since the design methods began in the early 1960s. In the table below some examples are shown, highlighting the early stages of design.

Table 2 Early stages of designing according to different authors (adapted from Ogat & Kremer, 2004)

Asimow (1962)	Dym and Little (2004)	Dieter (1991)	Ulrich and Eppinger (2000)	Pahl and Beitz (1996)
Feasibility study	Client statement	Recognition of need	Planning	Clarification of task
Preliminary design	Problem definition	Definition of problem	Concept development	Conceptual design
Detailed design	Conceptual design	Information gathering	System-level design	Embodiment design
	Preliminary design	Conceptualization	Detailed design	Detail design
	Detailed design	Evaluation	Testing and refinement	
	Design communication			

Note: The early stages are shown by the gray color.

Other contributions to the design process include Pugh’s Total Design (Pugh, 1991), which is more extensive and includes the marketing and selling of products. The Association of German Engineering (VDI) guidelines (VDI, 1993) are similar to Pahl and Beitz’s phases in design. Mechanical design (Ullman, 1992), the Taguchi method (Taguchi & Phadke, 1989) for quality and robust design, and axiomatic design by Suh (1990) are among those that have been recently reviewed (see Adams (2015) in Chapter 2). Some of the advantages and disadvantages of these systematic processes have also been studied in the past, especially their applicability and use in industry (see Günther & Ehrlenspiel, 1999)

and Tomiyama et al. (2009)). Among some of the advantages are that they are generally applicable to all kinds of design activities and for different products, services and systems. Additionally, these methods can be easily followed by practitioners. The disadvantages, however, are that most of these methods have not been updated to new technological advances and can also be easily misused to justify intuitive ideas (Tomiyama et al., 2009), as well as be considered less important in practice as compared to the product and technical drawings (Günther & Ehrlenspiel, 1999).

Furthermore, the scope of design research seems to have significantly expanded since the 1960s. For example, several new fields address user and experience design (Redström, 2006); the business side of design, design thinking and design management, has also contributed to the general field of design (Cooper, Junginger, & Lockwood, 2009). Other fields include service design (Goldstein, Johnston, Duffy, & Rao, 2002), ecodesign (Brones & de Carvalho, 2015), the simultaneous design of Product Service Systems (PSSs) (Morelli, 2006), and more recently design for sustainability (Ceschin & Gaziulusoy, 2016). This expansion seems to have broadened the scope from products to include services and now systems (ibid). The next section reviews fields of research that are relevant to environmental sustainability, namely ecodesign and Product/Service Systems.

2.3 Ecodesign

One of the earlier answers to include environmental sustainability in the design of products can be argued to be ecodesign. According to ISO 14006:2011, ecodesign is the “integration of environmental aspects into product design and development, with the aim of reducing adverse environmental impacts throughout a product’s life cycle” pp. 2. (International Organization for Standardization, 2011). Similarly, Ceschin and Gaziulusoy (2016) suggest that “the overall goal of ecodesign is to minimise the consumption of natural resources and energy and the consequent impact on the environment while maximising benefits for customers” pp. 121-122.

Ecodesign seems to have its roots in Victor Papanek’s (1972) early and continuous critique of a consumerist society, and especially the role of designers (H. Lewis, Gertsakis, Grant, Morelli, & Sweatman, 2017). Since its early beginnings in the early 1990s, ecodesign has seen multiple contributions and it is recognized as a well-developed field of research (Hollander et al., 2017). Pigosso et al. (2016) identified around 350 publications between 1993 and 2015 dealing with tools and methods related to ecodesign. While the term ecodesign is widely used in the academic literature, other terms such as design for environment, or DfE, are used primarily in the United States (Brones & de Carvalho, 2015). In the UK, environmentally conscious design seems to be a more familiar term (see Argument et al., 1998). In German-speaking countries, the terms ökodesign, ökoeffizienz and ökologisches design have been used in the past (see Tischner, 1996), and in France the term éco-conception is also often encountered (see Grisel & Duranthon, 2002). Other similar terms include design for lifecycle, or DfLC, green design (Kutz, 2015) and environmentally sustainable design (ISO 2011).

Publications regarding ecodesign have ranged from success factors (Johansson, 2002) to tools used in practice (Knight & Jenkins, 2009) to challenges in implementation (Dekoninck et al., 2016). Rousseaux et al. (2017) suggest that there is still a low uptake of such tools and methods. Reasons for this have been attributed to a lack of knowledge about the tools, a lack of specialized staff, unsuitable company size and a lack of cooperation between divisions in a company, among others. Poulakodou et al. (2014) also identified obstacles to the use of environmental tools; among these obstacles they find that the tools may be too vague, many tools may already be in use or the tools may require detailed information. Boks (2006) also reports several obstacles in the integration of ecodesign into product development, suggesting that there is a gap between ecodesign proponents and executors, added to organizational complexities, a lack of cooperation, a lack of market demand, and goals and vision.

Therefore, Lindahl (2006), suggest that methods and tools should, for example, be easy to understand: intuitive, logical and easy to communicate. Adjustable to different contexts: a method must fit the company's way of working. And not too high requirements of data: requiring too much data before using a method or tool, among other important characteristics.

Furthermore, Hollander et al. (2017) suggest that ecodesign principles, strategies and methods are based on the here and now. Hollander et al. (2017) consider it a relative approach which is more suitable for the linear economy. They advocate for an absolute approach, which rather than optimizing what already exists should aim for an ideal state through widening the solution space and finding more innovative solutions. The reason for this is to increase absolute approaches where designers will need new guidelines, principles, strategies and methods.

2.4 Product/Service Systems

Another contribution to environmental sustainability can be seen in the Product/Service System, or PSS. The PSS has been the focus of extensive research since the early 2000s, due to its approach to fulfill customer needs in a sustainable manner (Mont, 2002). Its origins can be found in concepts such as dematerialization, transmaterialization and the service economy. For example, the concepts Factor 4 and Factor³ 10 developed during the early 1990s by researchers at the Wuppertal Institute in Germany pointed out that countries were using large amounts of natural resources, causing serious environmental problems (Ölundh, 2003).

Several literature reviews have discussed the PSSs. These reviews tend to look at how the PSS is defined (Baines et al., 2007), its benefits and barriers (Cavalieri & Pezzotta, 2012), where research is carried out and where it is published (see, for example, one of the latest literature reviews by Beuren et al., 2013 and Annarelli et al., 2016). Definitions about the PSSs abound in the literature, with the earliest usually attributed to Goedkoop et al. (1999) and Mont (2002). PSS can be defined as follows: "A marketable set of products and services, jointly capable of fulfilling a client's need" pp. 3. Goedkoop (1999), or "A system of products, services, supporting networks and infrastructure that is designed to be competitive, satisfy customer needs and have a lower environmental impact than traditional business models" pp. 123 Mont (2002).

Although the definition from Mont (2002) suggests that the PSS may lower environmental impacts, this is not always the case. For instance, Annarelli et al. (2016) suggest that sustainability has been losing its importance in the PSS, and Vezzoli et al. (2015) stress the sustainability aspect of the PSS in what they call the Sustainable Product Service System or S.PSS.

Contributions on how to design a PSS are often prescriptive and implemented in case companies. For instance, Morelli (2003) proposes a design process and a case study of a telecenter. In addition, Morelli (2006) provides more specific tools for designing a PSS through interaction maps, IDEF0 modelling and service blueprinting. Tukker and Tischner (2006) review several design methods, tools and projects aimed at providing clearer guidelines into how to design a PSS. A network called the *Sustainable Product Development Network*, or SusProNet, carried out different projects in this area between 1997 and 2002, for example MEPSS (Methodology development and Evaluation of a PSS) van Halen et al. (2005), HiCS (Highly Customerised Solutions) Manzini et al. (2004), ProSecCo (Product-Service Co-design) and Innopse (Innovation Studio and Exemplary Developments for Product-Service). The findings of the SusProNet suggested that much of the theory of PSSs was not well linked to business literature.

³ Factor 4 means to double wealth by halving resource use. Factor 10 focuses on reducing material intensity by a factor of ten (Robèrt, 2000).

Although PSS research has been increasing in recent years, the field is often criticized for lacking maturity and a coherent terminology (Van Ostaeyen, 2014). This is not surprising when looking at the many overlapping concepts such as the IPSO (Lindahl, Sundin, & Sakao, 2014), IPS² (Meier, Roy, & Seliger, 2010) and servitization⁴ (Baines, Lightfoot, Benedettini, & Kay, 2009), among many others.

Vasantha et al. (2012) review eight methodologies on how to design a PSS, while suggesting that these have been limited in their industrial practice. In this respect, Tran and Park (2014) provide a generic design methodology for a PSS to increase practicality and provide guidelines for designers and developers.

The delivery, contact with the customer or the marketing side of a PSS has also seen several contributions. For example, in the marketing literature Windahl and Lakemond (2010) provide an insight into how three firms in the capital goods industry provide integrated solutions in four categories: rental, maintenance, operational and performance offerings. In the engineering literature, Visintin (2012) provides a delivery framework for integrated solutions based on a firm in the printing industry. Finally, the product, use or result-oriented manners by Tukker (2004) are widely recognised in the PSS community as the main categories with which to deliver a PSS; however, so far the literature has reported limited uptake by industry (Cook et al., 2006). Therefore, the implementation and advice on how to efficiently design PSSs in industry remains limited (Clayton, Backhouse, & Dani, 2012). Paper I and Paper IV address these issues. Since the scope of this research is limited to the early phases, the table below shows how different authors have looked at this phase in PSS.

Table 3 Early and late phases of a PSS (adapted from Wallin et al., 2015)

Isaksson et al. (2011)	Clayton et al. (2012)	Brezet et al. (2001)	Aurich et al. (2006)	Morelli (2003)	Alonso-Rasgado et al. (2004)
Early phases					
Need phase	Project initiation	Exploration	Demands Identification	Value proposition	Understanding client needs
	Analysis	Policy Formulation		Market analysis	
Solution seeking	Idea generation and selection	Idea finding	Feasibility analysis	Product/service definition	Transfer intellectual property
Solution development	Detailed design	Strict development	Concept development	Use-case analysis	Simultaneous development of client needs and concepts
	Prototype the service		Service modelling	Tentative architecture	
Late phases					
Solution realization	Implementation	Realization	Realization	Test	
	Evaluation	Evaluation	Planning		
			Service test	Final definition	
Solution support			Local service adaptation		
Solution closure					

Note: The early phases are shown by the gray color.

⁴ PSS is known in relation to other terms in other disciplines, for example the term servitization is a recurrent theme in operations management and industrial marketing. The literature suggests that these disciplines have researched the transition observed in manufacturing companies from product centered to service oriented. Industrial examples of this servitization usually refer to companies like Rolls Royce, IBM and Xerox (Lay, 2014).

3 Analysis and Evaluation in the Early Stages of Designing

This section takes a more in-depth look at the main topic of this thesis, the analysis and evaluation in the early stages of designing. It begins by providing an overview of the area of engineering design, while later focusing on how these can be understood in this research. It then provides a classification of these two aspects in ecodesign, product/service systems and how these could impact resource-efficient offerings.

3.1 General view of analysis and evaluation

Bucciarelli (1988) suggests that designing can be seen by some experts as *the management of process*, one which focuses on the different participants within an organization and where designing aims at effective communication, organization for collaborative work and tools for decision making. This understanding differs from other perspectives, such as *artificial intelligence*⁵ (AI) and the *teaching of design*. Bucciarelli (1988) argues that in the AI community, the interest lies in developing computer tools to assist engineers looking at design as a *cognitive process*.

In the teaching of design, the attempt is to model designing from beginning to end with a *block diagram*, an orderly sequence of steps where design moves from one block to the other and where there are iterations. According to Bucciarelli (1988), the teaching of design is a more mechanical view which overlooks the uncertainty and ambiguity of real design, while the AI perspective relies on individuals being rational, which then misses the differences of values among designers and the dynamic change of constraints and views. To Bucciarelli (1988), designing is a social process.

Nevertheless, the normative approach to analysis and evaluation of design has been largely discussed in the literature. Important contributions are summarized in the next table, where analysis and evaluation are highlighted.

⁵ In artificial intelligence, one of the most important contributions is John Gero's FBS framework, also seen in Table 4 in parentheses. For a detailed review, see Gero and Kannengiesser (2004).

Table 4 Design activities (adapted from Sim & Duffy, 2003)

Design activity	Hubka (1982)	Pahl & Beitz (1996)	Pugh (1991)	Suh (1990)	Ullman (1992)	Ulrich & Eppinger (1995)
Design Definition Activities (Function to Form/Structure)						
Abstracting	X	X		X	X	
Associating	X	X	X			
Composing		X			X	
Decomposing	X	X		X	X	X
Defining	X	X	X			X
Detailing	X					X
Generating	X	X	X	X	X	X
Standardising	X	X	X			X
Structuring/Integrating	X					X
Synthesising	X	X	X	X	X	X
Design Evaluation Activities (Form/Structure to Behaviour/Effects)						
Analysing	X	X	X	X	X	X
Decision making	X	X	X	X		X
Evaluating	X	X	X	X	X	X
Modelling	X	X	X		X	
Selecting	X	X			X	X
Simulating	X				X	
Testing/Experimenting	X	X	X			X
Design Management Activities						
Constraining		X				
Exploring						X
Identifying	X	X	X	X		
Information gathering	X	X	X		X	X
Planning					X	
Prioritising						
Resolving						
Searching	X	X			X	X
Selecting	X	X	X		X	X
Scheduling		X	X			

Note: Analysis and evaluation are shown by the gray color.

Due to the many ways in which design evaluation activities can be looked at, many contributions have been proposed in the past. Decision making, modeling, selecting, and so on all seem to be part of the general analysis and evaluation of design. For example, in the field of AI, Gero (1990) suggests that analysis deals with the behaviour of objects, while evaluation is a comparison between alternatives. In AI, one can therefore think of analysis as the prediction of how an artefact (product, service or system) may behave according to a set of determined criteria (reliability, sustainability, costs, flexibility, feasibility, and so forth) (Gero & Kannengiesser, 2004; Hazelrigg, 1998). Evaluation, in turn, can be understood in the general field of design as the means by which one can compare alternative concepts (see, for example, how Dieter and Schmidt (2013) explain evaluation).

3.2 General methods for analysis and evaluation

Design evaluation activities as depicted in Table 4 seem to combine and use different terms interchangeably. In engineering projects, one of the earliest methods - which was later adapted to environmental costs - can be suggested to be life cycle costing (LCC) (Gluch & Baumann, 2004). In relation to design, Bieda (1992) provides an 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 Bieda (1992), LCC helps to promote teamwork between the engineering and business community.

Other methods relate to the fulfilment of multiple criteria. These are in the realm of the decision-making literature. Decision analysis methods can be classified into single objective decision making (SODM), subdivided into decision trees and influence diagrams; decision-support systems (DSS), which are largely used in software development; and finally, multi-criteria decision making (MCDM), which in turn can be divided into multi-attribute decision making, or MADM, and multi-objective decision making, or MODM (Zhou, Ang, & Poh, 2006). An example of MCDM is found in Cheaitou and Khan (2015), who make use of MCDM with qualitative and quantitative factors to select suppliers. They also make use of the analytical hierarchy process (AHP) and optimization to rank and select suppliers according to specific criteria. Furthermore, Garetti et al. (2012) conducted a state-of-the-art review of existing solutions implementing life cycle simulation (LCS). They provide different guidelines or preferred characteristics for LCS: modularity, 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 clearly defining 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 AHP, which is used for selecting among alternatives, especially in the early phases of design. The authors also highlight the importance of systems engineering and sensitivity analysis in decision making and the technique for order of preference by similarity to ideal solution (TOPSIS).

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 for their actions in an uncertain environment. The following table provides some of these methods.

Table 5 Tools used in decision making (adapted from the National Research Council, 2001)

Approach	Tools		Primary Basis							Ratings by the Committee (1=low; 5=high)				
	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		
	Decision Matrix			X			X	4	1	2	4	5		
Qualitative	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				3	2	3	4	3		
Statistical	PLS				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		

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 above along with the ease of use according to panel experts.

The Council proposes the above categories as a discussion platform, arguing that not all are actual tools but rather 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.

3.3 Analysis and evaluation in this research

Analysis and evaluation can be easily confused since they can be used interchangeably. Methods for analysis, therefore, can depend on the criteria that a designer makes use of. The criteria in this research will come from the interdisciplinary literature in engineering design, marketing (see Papers I and IV) and the environmental sciences. Evaluation and decision making in engineering design are usually addressed together (see, for example, Dieter & Schmidt, 2013, Chapter 7 or Otto & Wood, 2001, Chapter 11). Methods for evaluation and decision making are largely based on a matrix format, where several designs are compared. For instance, the Pugh Chart (1991) compares each generated concept to a reference or *datum* concept to determine if the concept in question is better or worse than the datum concept. Moreover, it is also common to find in the evaluation of design a weighted decision matrix (Dieter & Schmidt, 2013), where ratings based on a predefined criteria are added up and the concept with the highest rating is selected. Additionally, Dorst and Dijkhuis (1995) conclude that addressing design as a rational problem-solving process is apt when a problem is clear-cut and where strategies are available to follow while solving the problem. In contrast, Dorst and Dijkhuis (1995) mention that design as a process of reflection-in-action works well in the conceptual phase, where there are no standard strategies. Based on the literature, what has been observed in practice so far and Dorst and Dijkhuis' insights, the following view of analysis and evaluation is brought forward. **Analysis** entails problem-solving tools and skills like mathematical equations, modeling and simulation. It starts early in design, but increases in complexity as more information becomes available and the project is allocated resources. The tools employed in analysis become more sophisticated as time progresses during the project to ensure an efficient outcome. **Evaluation** also starts early in design, but with little information. Allocation of resources begins but uncertainty in the final outcome is high. It requires knowledge and experience rather than mathematical equations to ensure an effective outcome. The figure below graphically shows how analysis and evaluation can be understood.

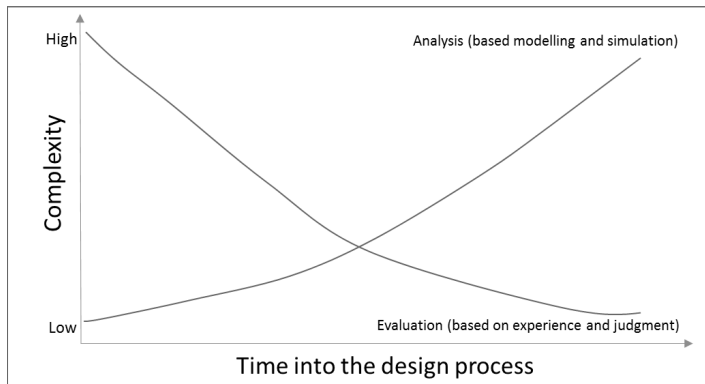


Figure 4 Analysis and evaluation in the design process (author's own)

3.3.1 Analysis and evaluation in ecodesign and PSS

There does not seem to be one single way in which to classify different methods, tools or support. For instance, Baumann et al. (2002) reviewed more than 150 tools in environmental product development and divide them into frameworks, checklists and guidelines, rating and ranking tools, analytical tools, software and expert systems and organizing tools. Bovea and Pérez-Belis (2012) provide a taxonomy of ecodesign tools divided into three large categories, namely methods for evaluating the environmental impact (subdivided into qualitative, semi-qualitative and quantitative techniques), tools for integrating environmental aspects into the design process (for example, quality function deployment for the environment, or QFDE, and life cycle assessment, or LCA), and methods for integrating environmental and other traditional requirements (for instance, design matrix, QFD and FMEA). Schöggel et al. (2017) categorize tools for sustainable product development into qualitative (ten golden rules, ten UNGC principles and method for sustainable product development, or MSPD) semi-qualitative (ecodesign checklist, ecodesign pilot and UNEP design for sustainability impact profile) and quantitative (streamlined and full LCA and Ford of Europe's Product Sustainability Index). In this thesis, a classification is made based on analytical and evaluation tools as expressed in Figure 4. Analytical tools are more quantitative, and require more precise data and information while evaluation tools are more qualitative, and are based on experience and judgment.

3.3.2 Ecodesign

One of the earlier reviews of analytical environmental tools is provided by Wrisberg et al. (2002). The authors conduct a thorough review of analytical environmental tools for environmental design and management. Their contribution is part of the European environment and climate program CHAINET, carried out between 1997 and 1999. Their review divides tools into three elements: *analytical*, which give outputs of the consequences of a choice; *procedural*, which function as a way to reach a decision; and *technical*, which support all previous tools. Among their review of tools are cost benefit analysis (CBA), cost effectiveness analysis (CEA), material flow accounting (MFA), life cycle assessment (LCA), environmental risk assessment (ERA) and environmental input output analysis (env. IOA). These tools are usually based on extensive information to quantify environmental impacts. Some of these methods are usually described as "accounting" methods (Finnveden & Moberg, 2005).

Ecodesign tools addressing evaluation follow a different approach. The use of checklists, guidelines, matrices, and principles seem to be a common feature. Environmental effect analysis (EEA) (Lindahl, 2000), the ecodesign checklist method (ECM) (Wimmer, 1999) and the ten golden rules (Luttrupp & Lagerstedt, 2006) are just few examples of evaluation.

However, Rossi et al. (2016) point out that most of the previous literature has focused on classifying ecodesign tools to foster their use rather than their barriers for implementation. For example, Byggeth

and Hochschorner (2006) review ecodesign tools in trade-off situations, concluding that 9 out of the 15 tools reviewed do not provide support in these types of situations (when alternative solutions emphasize different aspects). Additionally, Bovea and Pérez-Belis (2012) provide a taxonomy of ecodesign tools with the objective of integrating environmental requirements into the product design process. Moreover, Rossi et al. (2016) present barriers, weaknesses and possible improvement of ecodesign tools; among the most common barriers are specialized knowledge needed, the high number of tools already available, the lack of staff experience and high specificity. Among the possible improvements suggested by Rossi et al. (2016) are links to economic aspects, simple software without expert knowledge, inclusion of market aspects, compliance with ISO 14040 and simplification of procedure to be applied easily in the design team. These recommendations will be taken into account when developing the support for resource-efficient offerings.

3.3.3 Product/Service System (PSS) design

The PSS makes extensive use of modeling and simulation for the analysis of offerings. 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 (see, for instance, An et al., 2008 and Kim & Yoon, 2012).

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 some of the design methods found in the PSS literature. Heterogeneous IPS² by Meier and Massberg (2004) is also worth mentioning, as these authors attempt to model the PSS. The design process for the development of an integrated solution by Morelli (2002) is also an important contribution. Moreover, analysis and evaluation of the PSS seems to be studied as a rational endeavor based on decision theory, a rational and mathematical approach in the larger engineering design community (see, for example, Suh, 1990; Lewis et al., 2006, Hazelrigg, 2012 and Chen et al., 2012). Clayton et al. (2012) report on past approaches to the design of PSSs. They describe the following methods: DES, which stands for designing eco-efficient services by Brezet et al. (2001); AEPSS, which refers to the Austrian eco-efficient PSS project; MEPSS, which is methodology for PSS innovation; Kathalys, which corresponds to a method by Luiten et al. (2001); DEP, which is the design exploration process by Morelli (2002, 2003); and finally SSD, which is the service system design approach by Kar (2010). These methods are shown in Table 6.

Table 6 Design phases of PSSs in different projects (based on Clayton et al., 2012)

Phase	DES	AEPSS	MEPSS	Kathalys	DEP	SSD
<i>Project Initiation</i>	X	X				X
<i>Analysis</i>	X	X	X	x	x	X
<i>Idea generation and selection</i>	X	X	X			
<i>Detailed design</i>	X	X	X	x	x	X
<i>Prototype the service</i>	X			x	x	X
<i>Implementation</i>	X	x	X	x		X
<i>Evaluation</i>	X	x				X

Note: Projects denoted by a bold, large “X” are those that recognize a phase according to Clayton et al. and that provide activities for that phase. Projects denoted by a small “x” are those methods that recognize a phase but do not break it down into different activities

Those phases of interest to this section are analysis and evaluation. Clayton et al. (2012) suggest that analysis refers to “the identification of opportunities for the design of a PSS that will overcome customers’ needs or pain” pp. 283., while evaluation is understood as “an assessment of the worth of PSS” pp. 283. The findings of Clayton et al. suggest that PSS design is not complete, since the project initiation phase lacks adequate inputs and the evaluation phase lacks both inputs and outputs. Some tools for analysis of PSSs are Service CAD by Komoto and Tomiyama (2008) and Service Explorer by Sakao and Shimomura (2007). Moreover, Erkonyucu et al. (2010) and Erkoyuncu et al. (2013) have looked at uncertainty while designing PSSs, which can be considered a form of analysis.

Finally, Nikander et al. (2014) review important contributions in the research of analysis and evaluation activities in Scandinavia. Some of these contributions include Kihlander (2011), who concludes that designers make little use of formal (normative) decision making in concept selection. Lopez-Mesa and Bylund (2011), who studied concept selection at Volvo Car Corporation, found little use of structured methods (followed step by step) in design practice while suggesting that designers prefer guidelines or the adaptation of these methods to their particular needs. Laakso and Liikkanen (2012) found that design practitioners use informal, ad hoc methods. Other contributions include Eriksson (2009) and Derelöv (2009). Eriksson (2009) studied collaborative decision making in product development where, among other findings, his results point at low awareness of decision making as an important factor in product development, which in turn can affect decision-making methods. Derelöv (2009) looks at the evaluation of design concepts; he develops a design methodology for the biotechnology sector through modeling and optimization.

4 Methodology

Chapter 5 proposes that knowledge production for sustainability is in need of new ways of researching, studying and conducting design. Later in this chapter the methodology, methods, and techniques used in this research and the appended papers are also described.

3.1 Knowledge from early times to current practice

Early philosophers such as Plato and Aristotle attempted to study human knowledge in order to understand how it can be organized and best acquired (Weingart, 2010). Since then, the acquisition and production of knowledge has gone through many changes. For example, the scientific revolution of the XVII century and the birth of modern science is usually attributed to Francis Bacon and the scientific method (Van Doren, 1991). This marked a change of paradigm, where dogma and beliefs were replaced by rationality. The enlightenment marked another turning point, when empiricism and skeptical views added a new dimension to knowledge.

Weingart (2010) argues that the accumulation of knowledge and the need to classify it led to disciplinary guilds to secure a monopoly of knowledge through disciplinary associations, educating students and certifying them after successful completion. Weingart (2010) suggests that the natural and social sciences have existed in their present form as disciplines for merely 200 years. This takes us to today's disciplines that have their own methods, tools and knowledge production. In design, the approach to knowledge production can be looked at from a design science perspective⁶, or in other words, what a researcher needs to know for doing design and for inquiring about design.

Since this research is transdisciplinary, a pragmatic and reflexive paradigm is recommended (Bawden & Allenby, 2017; Martens, 2006). The table below shows different paradigms. Pragmatism is the one used in this research.

⁶ Other ways to inquiry about knowledge in design exist, for example, information systems for reuse of information in design and differences between the needs of novice an experienced practitioners (Cross 2006).

Table 7 Research paradigms (adapted from Wahyuni, 2012)

Fundamental beliefs	Research Paradigms			
	Positivism (Naïve Realism) Rationalism	Postpositivism (Critical Realism) Empiricism	Interpretivism (Constructivism)	Pragmatism
Main representatives ⁷	Comte, Bacon, Espinoza, Leibniz, Kuhn, Polya, Lakatos.	Descartes, Locke, Hume, Popper (skeptics)	Feyerabend, Wittgenstein	Piercy, Dewey
Ontology: the position on the nature of reality	External, objective and independent of social factors	Objective. Exist independently of human thoughts and beliefs or knowledge of their existence, but is interpreted through social conditioning (critical realist)	Socially constructed, subjective, may change, multiple	External, multiple, view chosen to best achieve an answer to the research question
Epistemology: The view on what constitutes acceptable knowledge	Only observable phenomena can provide credible data, facts. Focus on causality and law-like generalizations, reducing phenomena to simplest elements	Only observable phenomena can provide credible data, facts. Focus on explaining within a context or contexts	Subjective meanings and social phenomena. Focus upon the details of situation, the reality behind these details, subjective meanings and motivating actions	Either or both observable phenomena and subjective meanings can provide acceptable knowledge. Focus on practical applied research
Axiology: the role of values in research and the researcher's stance	Research is undertaken in a value-free way; the researcher is independent of the data and maintains an objective stance	Research is value laden; the researcher is biased by world views, cultural experiences and upbringing	Researcher is part of what is being researched, cannot be separated and so will be subjective	Researcher adopts both objective and subjective points of view

⁷ Based on own readings of Hay (2008), Weingart (2010) and Chalmers (2013).

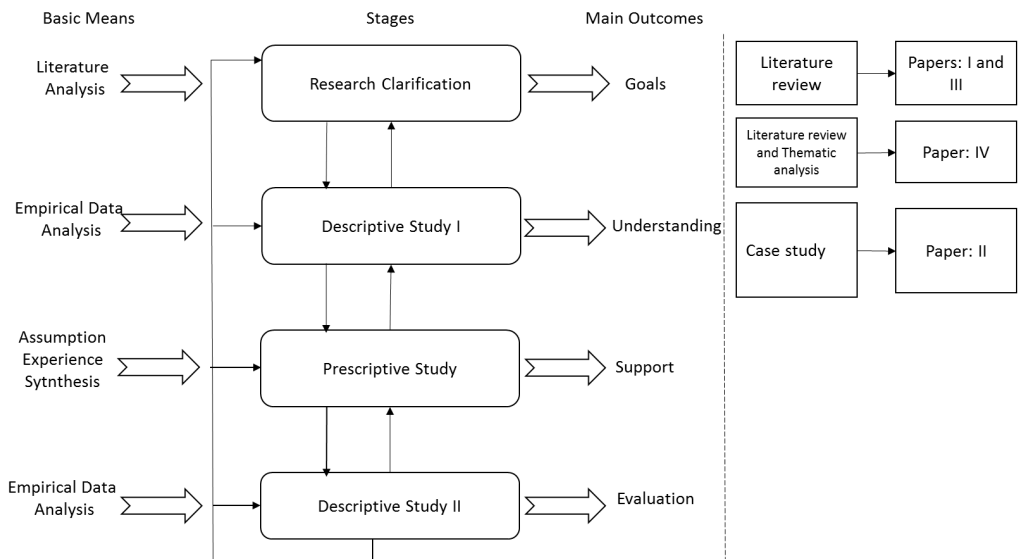
3.1.1 Knowledge in engineering design research

In *Designerly ways of knowing*, Cross (2006) suggests that research of design is done through the following methods: interviews with designers, observations and case studies, protocol studies, reflection and theorizing, and simulation trials. Each is explained below.

Interviews with designers. In the field of design, these have usually been carried out with designers with a well-developed design ability and by using unstructured interviews to capture designers' reflections on processes and procedures they follow. **Observations and case studies.** These have usually focused on a specific project at a certain time. Participant and non-participant observations have been used, as well as artificially-constructed design projects. **Protocol studies.** This is a formal method applied to artificial projects. It is based on thinking aloud and relevant actions performed during a design task. It is a method that has been used with both students and experienced designers. **Reflection and theorizing.** There is significant history in design research to carry out theoretical analysis and reflection on the nature of design. **Simulation trials.** This is a relatively new method for AI researchers to simulate human thinking by using artificial intelligence techniques.

3.2 Methodology of this research

The methodology of this research is based on the design research methodology, or DRM, proposed by Blessing and Chakrabarti (2009). According to Blessing and Chakrabarti (2009), this methodology gives design research more rigor and a scientific basis, which are characteristics that had been criticized in the past. Figure 5 shows the steps followed in DRM.



Note: the right-hand side of the figure after the dotted line is added for this research.

Figure 5 Design research methodology (adapted from Blessing & Chakrabarti, 2009)

Within this methodology, several methods have been used and others will be utilized in the future. For research clarification and the Descriptive Study I, the literature review and case study methods were used. For the Prescriptive Study, a participatory approach (transdisciplinary) will be used. This will entail methods more in line with action research, participant observation and ethnographic methods to see how practitioners in organizations are actually working and how the support can match their needs.

3.3 Methods

The methods used during this research to capture data and information are qualitative. Qualitative methods are usually advised when they can provide useful information on complex phenomena, or when rich details regarding different stakeholders are needed (Johnson & Onwuegbuzie, 2004). However, some drawbacks still exist like time spent on data collection, that knowledge produced may not be applied to other situations, and that the results can be more influenced by the researcher than needed (ibid.)

The main qualitative methods used in this research (see Papers I, II and IV for the literature review method and Paper III for the case study method) are briefly explained below. As mentioned above, more participatory methods will be employed in future studies which are not yet part of this research.

Literature review: Webster and Watson (2002) suggest that a high-quality review covers relevant literature on the topic studied, and that it is not confined to a single research methodology, journal, or even geographic area. This implies that a literature review is concept-centric, and not regional or author-centric. Furthermore, Cronin et al. (2008) suggest that there are two types of reviews: a narrative or traditional review and a systematic one. The former summarizes a body of literature and has as its purpose to provide a comprehensive background for understanding current research and the significance of new research, while the latter is used to answer well-focused questions, and a timeline and databases will be selected to analyze and draw conclusions from it. In Papers I, II and IV, narrative and systematic literature reviews were followed. The keywords and journals selected for Papers I and IV were:

Keywords in Web of Science:

(TS=("product service system") OR TS=(product-service system) OR TS=(product/service system) OR TS=("product service systems") OR TS=(product-service systems) OR TS=(product/service systems) OR TS=("functional *product*") OR TS=("integrated *solution*") OR TS=("hybrid *offering*" AND "manufacturing") OR TS=("industrial *service*") OR TS=("system *solution*" AND "manufacturing") OR TS=("customer *solution*") OR TS=("marketing *solution*") OR TS=("after-sales service" AND "manufacturing") OR TS=("serviti?ation") OR TS=("service infusion") OR TS=("service engineering") OR TS=("service transition" AND "manufacturing") OR TS=("service *strateg*" AND "manufacturing") OR TS=(solution? provider?))

Selected journals in Engineering Design:

CIRP Annals - Manufacturing Technology, Computer-Aided Design, Computers in Industry, Design Studies, International Journal of Advanced Manufacturing Technology, International Journal of Computer Integrated Manufacturing, International Journal of Operations and Production Management, International Journal of Production Research, Journal of Cleaner Production, Journal of Engineering Design, Journal of Operations Management, and Research in Engineering Design, Proceedings of the Institution of Mechanical Engineers Part B-journal of Engineering Manufacture.

Selected journals in Marketing:

European Journal of Marketing, Industrial Marketing Management, International Journal of Research in Marketing, Journal of Business and Industrial Marketing, Journal of Business Research, Journal of Business-to-Business Marketing, Journal of International Marketing, Journal of Marketing, Journal of Marketing Research, Journal of Product Innovation Management, Journal of Service Management (formerly International Journal of Service Industry Management), Journal of Service Research, Journal of Services Marketing, Journal of the Academy of Marketing Science, Journal of Service Theory and Practice (formerly Managing Service Quality: An International Journal), Marketing Letters, Marketing Science and Marketing Theory)

For Paper II, the keywords were used only for the Journal of Cleaner Production to find out if there were different ways to understand the concept of transdisciplinarity. The keywords were:

Keywords in Web of Science:

((TS=("ecodesign") OR TS=("eco-design") OR TS=("design for the environment") OR TS=("design for sustainability")) AND (TS=("multidisciplinary") OR TS=("multi-disciplinary") OR TS=("interdisciplinary") OR TS=("inter-disciplinary") OR TS=("transdisciplinary") OR TS=("trans-disciplinary") OR TS>(*disciplin*)))

Thematic analysis. Braun & Clarke (2006) argue that thematic analysis is a preferred method when identifying, analyzing and reporting patterns or themes in qualitative data. This method, which relies on a series of steps to formulate and analyze different themes (Fereday & Muir-Cochrane, 2006), was used in Paper IV to see how engineering design and marketing were using each other's insights. The themes found and further detailed in appended Paper IV were business orientation, collaboration, cost aspects, flexibility, indicators, requirements, and services.

Case study. Case study research is especially useful when exploring a problem or phenomenon and later trying to build a theory (Voss, Tsikriktsis, & Frohlich, 2002). This method can have as techniques, documentation, interviews and participant observation among the most important data collection techniques (Tellis, 1997). However, some drawbacks of this method can be strong bias from the researcher, not knowing when to stop the case study and the validity of the findings (Voss et al., 2002).

The case study can be classified as a method that according to Yin (1994) has four stages:

1. design the case study,
2. conduct the case study,
3. analyze the case study evidence, and
4. develop the conclusions, recommendations and implications.

The case study method was utilized in Paper III as a single case study in which recommendations were highlighted and primarily directed at practitioners.

3.3.1 Data collection

Interviews. These are widely used when carrying out qualitative research, and when the skills of the interviewer play a big role in the quality of the data obtained. There are several types of interviews; three of these are called unstructured, semi-structured and structured (DiCicco-Bloom & Crabtree, 2006).

A difficulty when carrying out an interview is that there is a need to develop some *rapport* (DiCicco-Bloom & Crabtree, 2006), that is, familiarity between the interviewer(s) and respondent(s), although this may not always be achieved due to time and place constraints. Other drawbacks can be the coding of the interviews and the categories selected when coding, as well as the time needed for carrying out these activities.

Data collection in the form of unstructured interviews was used during this research for the case study in Paper III. Multiple face-to-face and Skype meetings were carried out with two employees involved in the design and pilot study of the support developed. Semi-structured interviews with other case companies will be published later in Stages III and IV of the DRM. These interviews will be complemented by participatory methods (participant observation or ethnography).

Documents. Robson (2011) advocates that documents primarily concern written text in the form of books, newspapers, magazines, and letters, and that in some instances this can extend to films, pictures and drawings. Journal articles by Ashby (2000) and Rangachari and Mierson (1995) provide guidelines on how to write and what to look for in a journal article, some of which are presented below.

Table 8 Some guidelines for analyzing journal papers (based on Ashby, 2000 & Rangachari & Mierson , 1995)

Abstract	Is the abstract intelligible?
Introduction	Did the authors indicate why the study was undertaken?
	What is the problem and why is it interesting?
	Was the background information adequate to understand the aims of the study?
Methods	Were the methods described in sufficient detail for others to repeat or extend the study?
	Have the authors indicated the reasons why particular procedures were used?
Results	Do the results obtained make sense?
	Are data presented clear?
Discussion	Were the objectives of the study met?
	Do the authors discuss their results in relation to available information?
References	Do the authors cite appropriate papers for comments made?
	Are references complete?

The above guidelines, as well as suggestions by supervisors and more senior colleagues were used when analyzing documents. This was especially important for the thematic analysis used in papers I and IV.

5 Results

This section begins with a summary of the appended papers, highlighting their results. It then presents knowledge gaps identified, and finally discusses how these papers are interlinked.

5.1 Summary of appended papers

5.1.1 Paper I

Brambila-Macias, S. A., Sakao, T., & Kowalkowski, C. (2016). Interdisciplinary Insights Found for Product/Service System Design. In *Proceedings of the DESIGN 2016 14th International Design Conference* (published)

Research questions: Which insights coming from the industrial marketing discipline have been utilized in the engineering design discipline, and vice versa? What has been the level of utilization of insights?

Summary: This conference paper suggests that current academic literature could benefit from an increase of interlinkages among engineering design and marketing to effectively support PSSs. This seems necessary, since the PSS falls into an interdisciplinary field of research where engineering design has mainly focused on the product and marketing on the customer. In this paper, interdisciplinary research is described as a unified understanding of a given issue, and therefore as something which can trigger progress in knowledge and excellence in research. Furthermore, several researchers in PSSs and product development have been critical of the lack of interdisciplinary work, and in some instances have suggested that there is lack of mutual respect between marketing and design.

Conclusion: The results show that insights across disciplines are low. This could mean that important insight, for example, rapid changes in the market or customer requirements could be overlooked by engineer designers, and likewise that marketers could be understating difficulties in the design process of new artifacts and most importantly how to service a product.

5.1.2 Paper II

Sakao, T., & Brambila-Macias, S. A. (2018). Do we share an understanding of transdisciplinarity in environmental sustainability research? *Journal of Cleaner Production*, 170, 1399-1403 (published)

Research question: (as title of letter to the editor). Do we share an understanding of transdisciplinarity in environmental sustainability research?

Summary: The *Journal of Cleaner Production* (JCLP) suggests that it is “an international, transdisciplinary journal focusing on Cleaner Production, Environmental, and Sustainability research and practice”. In this letter to the editor, the authors raise the question of what is meant by transdisciplinary and if there is a common understanding of it. The literature review carried out for this purpose shows that what is meant by transdisciplinarity is still contested. The authors then propose two ways to understand it. Transdisciplinary I is a more systemic discipline which was developed in order to address real and complex problems. Transdisciplinary II, or what is known as Mode 2 knowledge production, is participatory research between academia and industry to also address “real-world” problems.

Conclusion: The results show that transdisciplinarity in JCLP has been used in different ways, and the authors call for more discussion around this research approach. The importance of transdisciplinary research and its clarification are explained by the authors as important to overcome barriers to integration and communication among researchers. Moreover, project participants can exchange views with a common understanding of concepts. Ultimately, a lack of common understanding could also present difficulties when comparing and evaluating results.

5.1.3 Paper III

Brambila-Macias, S. A., Dahllöf, L., Eriksson, K., Sakao, T. (2018) Development of an environmental evaluation tool in the transport sector and its impact on decision making in the early stages of design. In Life Cycle Management Conference 2017 (accepted).

Research questions: How can an environmental evaluation tool towards sustainability be used more in practice at a large company? How can internal organizational needs be identified and addressed in order to develop an environmental evaluation tool towards sustainability? How could an environmental evaluation tool support decision making in the early stages of design towards sustainability?

Summary: This conference presents, through a case study, how a company in the transport sector developed a tool for environmental evaluation. The case study shows the working process of the case company to establish a useful tool. The company began by establishing a reference group from different departments, while also including the potential users and carrying out a pilot project. This was done to secure acceptance, obtain feedback and permit the actual use of the tool. The analysis of the case study shows that other companies could replicate this by a plan-do-check-act process. In the case company, this was done by first identifying an organizational need, while also taking into account other factors such as core company values and external requirements like ISO 14001.

Conclusion: The conclusion suggests that other companies could take several factors into account when developing such a tool. In this case, the establishment of a reference group could be beneficial. The purpose and potential users also need to be clearly identified. The outputs of the tool should serve as inputs to other processes, and these should translate into actions.

5.1.4 Paper IV

Brambila-Macias, S.A., Sakao, T. & Kowalkowski, C. (n.a.) Bridging the Gap between Engineering Design and Marketing: Insights for Research and Practice of Product/Service System Design. Submitted to a design journal (under revision after first review).

Research questions: To what extent have insights coming from the marketing discipline been used in the engineering design discipline, and vice versa? What are the implications of insights in marketing for engineering design in order to more effectively and efficiently design PSSs?

Summary: This literature review is based on Paper I, and it is extended to include what engineering design can learn from marketing; it also provides a research agenda. The results show implications for academics and practitioners researching or interested in providing PSSs. These implications come from insights identified in the literature, and are categorized into seven specific themes: business orientation, collaboration, cost aspects, flexibility, indicators, requirements, and services. Business orientation suggests that PSSs can benefit from strategic thinking. Collaboration argues that organizations may need to collaborate with unusual partners, such as their own competitors. Cost aspects highlight that there might be hidden costs when offering PSSs, such as resistance to change or retraining of staff. Flexibility focuses on the adoption of temporary teams during different stages of designing and delivering a PSS. Indicators refer to performance indicators to cover efficiency and effectiveness to reflect firm and customer value. Requirements suggest that the customer and provider could require adjustments prior to engaging in PSSs. In the services theme, it is argued that engineering design can rely on the vast knowledge in marketing on how to offer services successfully.

Conclusion: The importance of engineering design and marketing when designing a PSS suggests that there is a need for bridging the gap between these two disciplines. The themes summarized were used to provide insights for academics and practitioners aimed at providing a clearer guidance into PSS implementation in industry. These themes can also provide opportunities to further advance the understanding of how to effectively and efficiently design PSSs.

5.2 Knowledge gaps

The appended papers have shown that there are some gaps that need to be further addressed. These are:

Lack of interdisciplinarity in academic literature. Two of the disciplines studied were engineering design and marketing (Papers I and IV), but other disciplines, for example information and communication technology, business and management, or environmental science, could also enrich insights for successful implementation. The reason for this is to provide offerings that are both efficient and effective, meaning the use a minimal amount of resources while providing what the market or customer actually needs.

Need to clarify transdisciplinary approaches. Current uncertainty and complexity when designing resource-efficient offerings requires a transdisciplinary approach (Paper II). However, this seems to be poorly understood. A better understanding of this approach could mean different research methods, new tools and hopefully increased implementation in industry.

Low uptake of academic design methods in industry. This seems to still be the case for most support provided by academia (Paper III). There appears to be a gap in the literature regarding how to design support tools, and few researchers follow their own methods as suggested by Reich (2010).

5.3 Interlinkage

The appended papers are interlinked in a procedural manner. That is, their output was used as information and guidance for the other papers. This is shown graphically below.

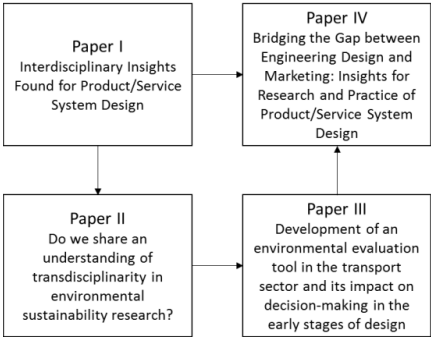


Figure 6 Interlinkage of the appended papers (author’s own)

Employing a literature review method, Paper I provided the literature necessary for Paper II. Studies in interdisciplinarity pointed at relevant literature for transdisciplinarity. Papers I and II provided some guidance on how to address the collaboration with industry to write Paper III. A participatory approach, rather than a “specialist” one, helped in organizing and describing the evaluation tool implemented at the case company. Finally, Papers I, II and III have provided experience and the framing of themes and insights for the writing of Paper IV.

6 Discussion

This chapter reflects on previous sections of the thesis. It provides a discussion on different environmental terms as well as my position in the field of engineering design methods. It then makes a comparison of ecodesign, PSS and resource-efficient offerings. Later in the chapter, I discuss the papers appended and provide arguments for the need of new knowledge for both how to design and carry out research in design.

6.1 Discussion of environmental concepts

There exists a large number of concepts in literature when addressing environmental challenges. In order to provide a critical analysis, the following section provides a short discussion.

The publication of *Our Common Future* in 1987 by Gro Harlem Brundtland has been heralded as a trigger to a *watershed* of environmental programs around the world for a sustainable future (Redclift, 2005). *The Brundtland Report*, as it is commonly known, called for more actions at the global, national and local levels (Sneddon, Howarth, & Norgaard, 2006); the term *sustainable development* was then defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” pp. na. (WCED, 1987). This definition has since then been largely discussed as well as criticized (Redclift, 2005). For example, weak versus strong sustainability (Neumayer, 2003), north versus south (De Kruijf & Van Vuuren, 1998) and differences in its interpretation have sparked continuous debate (Holden, Linnerud, & Banister, 2014). Moreover, sustainable development has been linked to the *triple bottom line* for businesses that balances economic prosperity, environmental quality and social justice (Jeurissen, 2000).

Sustainability and sustainable development have been used interchangeably in the past (Waas, Hugé, Verbruggen, & Wright, 2011). However, Harding et al. (2009) suggest that sustainability may be understood as the final destination or the ultimate goal, while sustainable development can be described as the path or framework to achieve sustainability. Geissdoerfer et al. (2017) suggest that the term sustainability originates from the French verb *soutenir*, meaning to hold or support, and define sustainability as “the balanced integration of economic performance, social inclusiveness, and environmental resilience, to the benefit of current and future generations” pp. 766. As can be noticed, the definitions of these two terms are similar, and hence it might not be a surprise that confusion can arise.

Moreover, in an effort to measure environmental sustainability the term *decoupling* was discussed in 2001 in the publication *Environmental Strategy for the First Decade of the 21st Century* by the OECD to break the link between the *environmental bads* and the *economic goods* (OECD, 2001). The concept of decoupling is further divided into *relative* and *absolute*: the former occurs when the rate of resources used is lower than economic growth, while the latter is when resource use declines, irrespective of economic growth rates (Fischer-Kowalski et al., 2011). Absolute decoupling is achieved through strategies of *transmaterialization* (*substitution*), *dematerialization* or *structural changes* (Azar, Holmberg, & Karlsson, 2002). These strategies are important, since they can influence how companies design or find new niches with their offerings.

Furthermore, the concept of *circular economy* (CE) has been shown to have limitations. From path dependency and lock-ins to the differences of cultural and social contexts when addressing waste (Korhonen, Honkasalo, & Seppälä, 2018), CE is not without its challenges. Moreover, its relation with sustainability is not well defined. Geissefoerfer et al. (2017) look at how this relation can be represented based on examples found in the literature. These relations are categorized as conditional, beneficial and of trade-offs. The first two are one-directional, and they suggest that CE is a condition, necessity or one of several solutions towards sustainability. The last, that of trade-offs, suggests that CE achieves a certain degree of sustainability but recognizes that it can also lead to less desirable outcomes, what we could call *rebound effects*. Finally, there seems to be confusion on the differences of fairly similar terms for CE such as *green economy* and *bioeconomy*. D’Amato et al. (2017) review these concepts and suggest that green economy is an *umbrella* concept that includes elements from circular economy and bioeconomy, and while both are resource-focused, green economy is based on ecological processes and is more inclusive of local level aspects such as eco-tourism and education. D’Amato et al. (2017) consider that all concepts are limited in questioning economic growth. The figure below shows D’Amato et al.’s view of these three concepts.

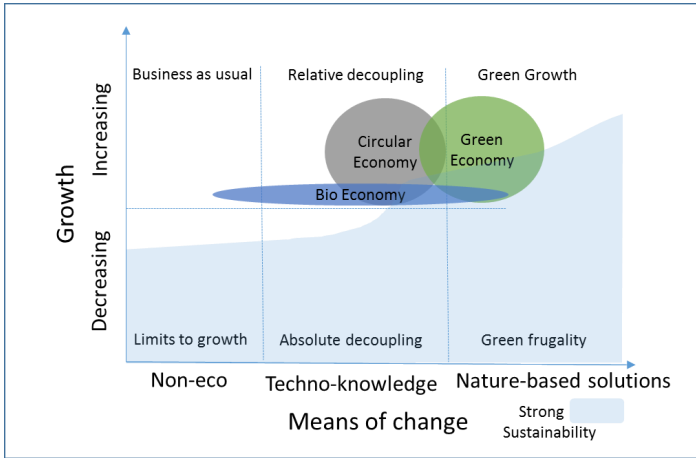


Figure 7 Differences between CE and other concepts (adapted from D’Amato et al., 2017)

The discussion above serves to describe what relevant key concepts mean in this research. The list below is a brief description my own understanding of key concepts.

- Sustainability can be interpreted as a vision for how we should live.
- Circular economy is described as a necessary paradigm shift towards sustainability.
- Decoupling is composed of different general strategies aimed at separating economic growth from resource depletion.
- Resource efficiency could be understood as a more detailed set of strategies for companies to implement efficient practices and to create value.

Resource-efficient strategies can then be supported by new business models, policies and design (Ijomah, McAloone, & Stahel, 2014; Milios, 2016). Figure 3 shows how these different concepts can be understood.

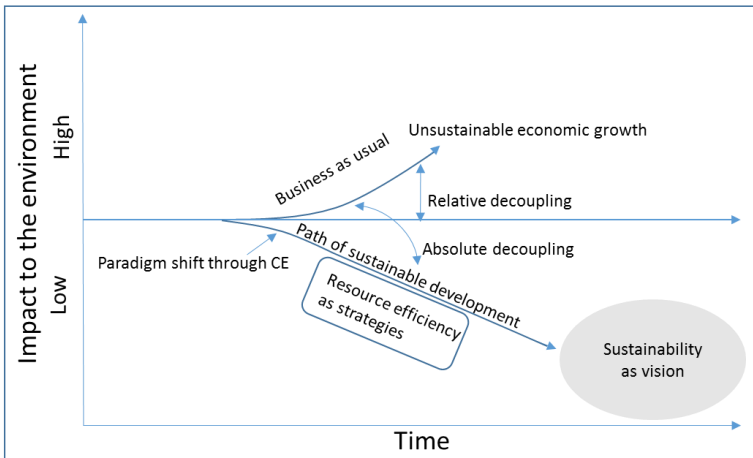


Figure 8 Representation of different concepts in environmental sustainability (author’s own)

6.2 Positioning in the field of engineering design methods

As previously mentioned, the study of design or design research has expanded in recent years. In “The Future of Design Methodology”, Birkhofer (2011) presents a collection of past contributions of design research and its different areas. The cream-colored boxes represent the research areas, while the larger ovals the main fields of research. I see myself in the field of design science, which looks at the *total knowledge of designing* (Hubka & Eder, 1996); this, however, does not mean that all areas will be studied in depth, but that relevant knowledge from different areas will be gained and applied in future research. The figure below shows how design science can be understood and my own positioning in the field, which is as “Design Scientist”. The reason for this is to play a double role: that of a researcher of design but also that of designing a support method or tool to support the analysis and evaluation of resource-efficient offerings. This is in line with Reich (2010) and his suggestion to use academic methods to create new tools.

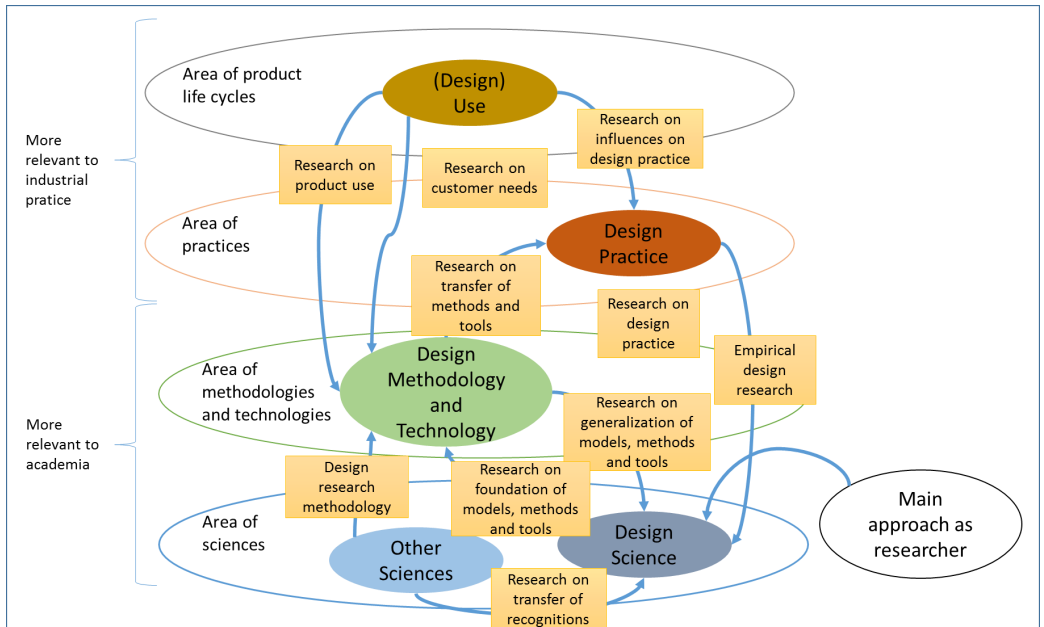


Figure 9 Typology of Design Research (adapted from Birkhofer, 2011)

6.3 Product/service systems, ecodesign and resource-efficient offerings

This section is dedicated to reflect on the differences and similarities among ecodesign, the PSS and resource-efficient offerings. From the review in Chapters 2 and 3, it becomes clearer that ecodesign is an approach to integrate environmental aspects into “traditional” design. In contrast, a PSS is a design process which currently provides some insights on how to design products and services from the beginning, it is prescriptive. Although many efforts have been made in the past, it seems that these efforts have yet to converge into a common understanding. Nevertheless, the PSS provides important insights to consider when providing a function or solution instead of a product or service independently. Therefore, it expands the scope and scale previously seen in ecodesign.

With regard to resource-efficient offerings, one could consider this a new field of research, one which involves multiple companies, stakeholders and transdisciplinarity when designing. It is different from

ecodesign and the PSS in that it expands even further the systems perspective to include other actors or stakeholders, and takes into account other factors such as business models and policies (Ijomah et al. 2014).

De Weck et al. (2011) provide a framework for the design of engineering systems, which they call a (re)visioning perspective. It includes scope and scale, function, structure and temporality. Scope refers to the number of aspects that need to be considered when defining the system. Scale involves the demography, number of components and other aspects to assess the system. Function refers to the purpose of the system, its *raison d'être*. Structure is the way in which elements of a system are interconnected. Finally, temporality addresses changes over time. Taking into consideration this (re)visioning perspective, the picture below shows how ecodesign, PSS and resource-efficient offerings can be understood. The picture shows that resource-efficient offerings increase the scope and scale first taken into account by ecodesign and PSS. It expands this even further (from function and structure) and also approaches problems from a more dynamic perspective (temporality). Similarly, Ceschin and Gaziulusoy (2017) suggest an evolution under design for sustainability going from a narrower perspective from the product to services, and finally socio-technical systems, which recognize multiple actors' interest and dynamics at a systems level. The figure below illustrates these different views.

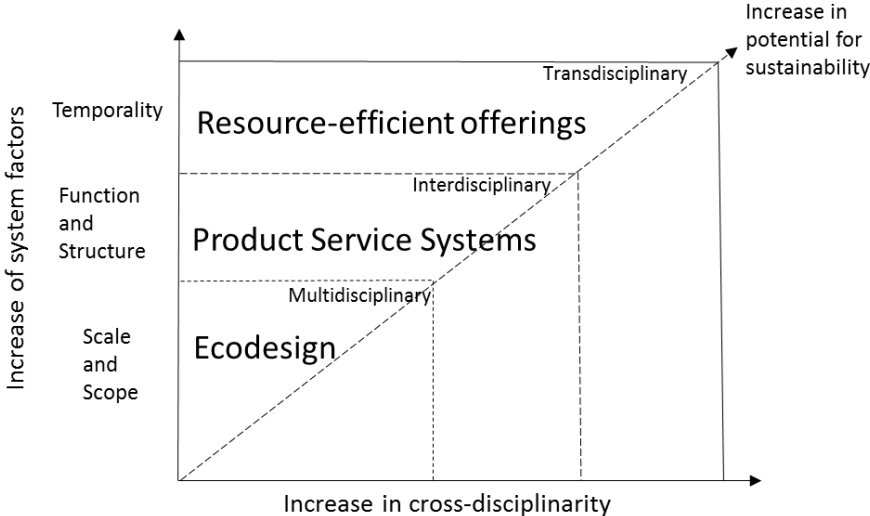


Figure 10 Relationship between Ecodesign, PSS and Resource-Efficient Offerings (based on De Weck et al., 2011 & Ceschin & Gaziulusoy, 2017)

6.4 Discussion of the appended papers

Paper I analyses interdisciplinary research between marketing and engineering design. **This seems to be insufficient** and necessary for the efficient and effective design of products, services and systems. Paper II implies that **transdisciplinary research** is necessary to address real-world problems; however, this type of research seems to be **poorly understood** and clarification is needed. Paper III shows how a company made use of their own knowledge and resources for **useful support in industry**. Research, however, shows a **lack of useful methods coming from academia**, and hence a need to bridge this divide. Paper IV suggests that there is **a need for more practical guidance on how to address the design of products and services in unison in practice, and its implications**. Knowledge from academia is presumed to lack practical guidance for industry. This is related to the case study presented in Paper III, which suggests that implementation needs to take into account the way in which companies

work internally. Support for companies needs to adapt to their everyday work and not the other way around, companies having to adapt to methods from academia. This means that deeper research should be carried out with companies as the “customers”, where researchers approach the design and development of methods as a product that needs to meet requirements to satisfy customers (companies) and users (engineers and other non-engineer positions involved in designing). The case study in Paper III is not sufficient to make further conclusions, and hence more research in this direction would provide knowledge into how other companies address analysis and evaluation in the early stages of designing. Complementary research can then provide robust evidence on how to best tackle the guidance, development and implementation of useful support.

The link among the papers appended in this licentiate shows that there is a promising and beneficial output when working in an interdisciplinary way (Papers I and IV). It is also shown that close collaboration with industry is necessary for addressing their practical problems (Paper III). In order to do this, academia first needs to address what transdisciplinary research entails (Paper II), with the aim of providing a common understanding across stakeholders and providing comparable results.

6.5 Need for new knowledge

De Weck et al. (2011) suggest that there has been an evolution in engineering and how challenges are addressed, and argue that there have been three epochs in engineering. The first one was an epoch of artifacts and great inventions, where around the late 1800s technical inventions, such as the automobile, the telephone and light bulb, were great inventions of artifacts. The second epoch, in the early 1900s, demanded greater awareness of a systems perspective, where automobiles were part of a large network of highways, telephones were part of the larger switch network and the light bulb part of the electric power grid. Finally, the current and third epoch is a more complex system where automobiles and highways are seen as *transportation systems* which include air, rail, road, water transportation and GPS navigation and satellites. The telephone and switch networks are part of a *communication system* which is connected to the internet, SMS, e-mails, etc. The light bulb and the electric power grid now make up part of a larger system, an *energy system* composed of coal, gas, oil and renewables. De Weck et al. (2011) make the argument that today’s engineers need to think of *engineering systems* to account for externalities, for example traffic jams and pollution when designing automobiles, and even anticipate changes to the system. This can be done by analyzing different alternatives; in the case of transportation systems, this means making use of tools like the Intelligent Transportation System, or ITS, along with the participation of stakeholders and considering externalities in energy, environment, noise and urban impact.

Similarly, in *DesignX: Complex Sociotechnical Systems*, Norman and Steppers (2015) argue for new skills for designers, those that can tackle complexity by having a broad knowledge including economics, law, environment and engineering, among other things. They call for *system designers*, those who can design, for example, school programs and healthcare systems, and who can manage complex problems through satisficing and not optimizing.

These systemic views, I believe, also have an impact on how research about design is performed. In this case, the characteristics of the support provided would need to be pragmatic, transdisciplinary, systemic, have a life-cycle approach, strategic and able to deal with increasing complexity. These characteristics are also reflected in the next table, which shows the response to environmental impacts in the last decades and which is aligned with what De Weck et al (2011) and Norman and Steppers (2015) have suggested.

Table 9 Response in the last decades to human impact on the environment (adapted from Harding et al., 2009)

Approach to ...	1970s	1990s	2010s
Decision-making	Linear decision-making, mainly informed by scientific and technical expertise	More open decision-making through bargaining and negotiating competing interests	Adaptive decision-making through collaborative learning
Mode of Governing	Hierarchical modes of governing - one-way flow of information	Inform and consult with key stakeholders	Broader engagement of community and co-production of policy through forming networks and unusual alliances
Planning	Short-term reactive	More proactive - anticipate impacts and take precautionary responses	Steering long-term change - accepting and dealing with complexity, ambiguity and uncertainty
Environmental Impact Assessment	Through policy Piecemeal Local impacts Short temporal scale	Through regulation Cumulative Regional impacts Longer temporal scale	Through regulation Cumulative and strategic Ecosystem to global (depending on the issue) Intergenerational
Form of Knowledge	Siloed and reductionist	Multidisciplinary but not integrated	Transdisciplinary
Breadth of Knowledge	Knowledge about the environment Technical and scientific expertise (technocracy)	Knowledge about the environment Physical science meets social and economic knowledge	Knowledge for sustainability Emphasis on capacity building and bringing together multiple perspectives - different ways of knowing and doing
Application of Tools	Narrow range of biophysical, technical and economic tools and models	Wide range of tools to inform and assist environmental management and for decision support	Continuing expansion of tools to serve broader roles - emphasis on integration in their use; broader recognition in their limits in use
Pollution Control	End-of-pipe	Source control	Systems thinking

Additionally, as a result of the use of transdisciplinary research the following table is adapted from Schön (1984) as an example of how a researcher in design (in this case myself) would need to change the research approach.

Table 10 The new way of thinking in transdisciplinary research (adapted from Schön, 1983)

Expert Researcher in a Discipline	Reflective Researcher in Transdisciplinarity
I am presumed to know, and must claim to do so, regardless of my own uncertainty.	I am presumed to know, but I am not the only one in the situation to have relevant important knowledge. My uncertainties may be a source of learning for me and for them.
Keep my distance from the client, and hold onto expert's role. Give the client a sense of my expertise, but convey a feeling of warmth and sympathy as a <i>sweetener</i> .	Seek out connections to the client's thoughts and feelings. Allow his/her respect for my knowledge to emerge from her/his discovery of it in the situation
Look for deference and status in the client's response to my professional persona.	Look for the sense of freedom and of real connection to the client, as a consequence of no longer needing to maintain a professional facade.

7 Conclusion and future research

This section presents conclusions of the research, and how Stages III and IV of the design research methodology (DRM) will be carried out during subsequent stages. These stages will include the implementation of the support and the validation by the users at the researched companies. Future research, in the form of planned publications and some lessons learned, are also provided.

7.1 Conclusion

This licentiate thesis began by providing some important historical milestones of awareness and international efforts to diminish human impact to the environment. Next, an overview of design methods aimed at providing a better understanding of the field and their use in the literature. From the initial methods of the 1960s to today's efforts in the form of ecodesign and product/service systems, designing is more important than ever to help companies diminish their impact to the natural environment.

The activities of analysis and evaluation in the design process were also described and put into context, namely, that analysis is a more structured, algorithmic, data driven process while evaluation relies more on expert judgment and experience. Moreover, the literature review also included different methods used for analysis and evaluation in the early stages of designing. These are usually provided in matrix form, and in the case of ecodesign these seem to be in the form of checklists and guidelines in the early stages, while LCA and similar methods are used for later stages. In PSSs, analysis and evaluation seem to be coupled more to modelling and simulation.

The methodology used in this research follows the design research methodology, which goes from a review of the literature to clarify research to the empirical data collection and subsequent development of support and evaluation of it in practice. The subsequent chapters on the methodology and results showed that first, important insights can be obtained through literature reviews and a case study, which are both descriptive exercises and second that important gaps are still prevalent in the engineering design literature, more specifically, methods coming from academia have a low uptake in industry. A need for a different approach to research, as well as education and implementation in methods seems necessary. Co-creation of methods using a transdisciplinary approach where researchers *facilitate* the creation of a tool or method seems to be the way forward. Knowledge from other disciplines relevant to the design of product/services also seems to provide a more inclusive design for efficient processes and effective results.

The discussion chapter provided a deeper analysis in what is meant by environmental terms. Sustainability is understood as a vision of how we should live, the circular economy as a paradigm shift necessary towards sustainability, and decoupling as an overall strategy aimed at separating economic growth from resource depletion. Resource efficiency could be understood as a more detailed set of strategies

The results so far confirm previous findings, mainly that companies use ad hoc methods that answer better to their needs, and that an effort for closer collaboration between academia and industry could be beneficial. It also shows that in order for this collaboration to produce fruitful benefits, inter and transdisciplinary research presents challenges that need to be addressed and clarified.

Regarding research question I: **How is analysis and evaluation carried out during the early stages of designing resource-efficient offerings in industry?** addressed in Paper III, shows how a company in the transport sector included users and a pilot project to test the usefulness of an evaluation tool. However, more research would provide richer data to provide more robust and significant results in order to provide suggestions applicable to a wider context. Research Question II: **What knowledge is needed to develop useful support for the early stages of designing resource-efficient offerings in industry?** addressed in Papers I, II and IV. suggests that inter and transdisciplinarity present challenges, but that these would provide a common understanding and a bridge across disciplines. Important insights could benefit academia and industry.

7.2 Future research

Future research will address effectiveness as well as efficiency. Input from the disciplines of marketing and environmental management will help in developing support for manufacturing companies for resource-efficient offerings. Moreover, the usefulness of the support that will be developed will be obtained from participatory research and industry feedback. This will comprise part of Stages III and IV of the design research methodology.

Furthermore, detailed information on current operations based on interviews will be analyzed, and the differences between needs for useful support between large companies and SMEs (where there seems to be a gap in the literature) will be a central point in future publications.

Moreover, future research will also make use of other methods such as protocol analysis to complement findings in the field. The method of participant observation or ethnography will be used to establish a closer relationship with potential users of the support provided. A list of future research themes is provided below.

- A) An investigation of how experienced practitioners perform analysis and evaluation in designing REES (based on interviews and protocol analysis).
- B) A comparison of analysis and evaluation of the conceptual design stage between large and small enterprises (based on interviews).
- C) Development of support for analysis and evaluation (with the empirical result of application at a company).

This section also provides space to reflect on what I have learned so far. During the research, important challenges became apparent and some lessons have been learned. The challenges range from novice research practice, not only in studying design, but also in carrying out an inter and transdisciplinary approach.

One lesson learned is **communication** with relevant stakeholders, for example, company representatives and researchers from other fields who are not familiar with the circular economy and other related concepts. The plethora of definitions and how different stakeholders interpret them has proven to be a challenge, and clear definitions are therefore necessary.

Another lesson concerns the **expectations** of the output of this research. For instance, companies seem to expect very applicable outputs from the start, and fellow researchers seem to place greater value on theories or frameworks than their application. To achieve a balance that is both rigorous for researchers and relevant for industry, a focus on insights from both the literature and industry is necessary.

Still another lesson is **fatigue of methods**, as the literature suggests that the applicability of methods coming from academia has been limited. Instead of talking about methods I have in many cases talked about **support or aid**, and addressed the company needs rather than academic prowess.

A final lesson learned to note is **mindset**, since companies might be reluctant to change due to path dependency, risks involved and overall buy-in of new support; hence, close collaboration to address their needs is necessary.

This marks the end of this licentiate thesis, but the beginning of more research which will focus on usefulness and relevance for industry while also being rigorous for academia.

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Appendix I Paper I: Brambila-Macias, S. A., Sakao, T., & Kowalkowski, C. (2016). Interdisciplinary Insights Found for Product/Service System Design. In *DS 84: Proceedings of the DESIGN 2016 14th International Design Conference* (published).

Appendix II Paper II: Sakao, T., & Brambila-Macias, S. A. (2018). Do we share an understanding of transdisciplinarity in environmental sustainability research? *Journal of Cleaner Production*, 170, 1399-1403 (published).

Appendix III Paper III: Brambila-Macias, S. A., Dahllöf, L., Eriksson, K., Sakao, T. (2018) Development of an environmental evaluation tool in the transport sector and its impact on decision-making in the early stages of design. In *Life Cycle Management Conference 2018* (accepted).

Appendix IV Paper IV: Brambila-Macias, S.A., Sakao, T. & Kowalkowski, C. (n.a.) Bridging the Gap between Engineering Design and Marketing: Insights for Research and Practice of Product/Service System Design Submitted to a design journal (in revision after the first review).

Papers

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