Support for the conceptual design stage of effective and resource-efficient offerings

A pragmatic and cross-disciplinary approach

Sergio A. Brambila-Macias

Linköping Studies in Science and Technology.

Dissertation No. 2098

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Cover page

The figure on the cover page shows that design researchers are also designers of support. As designers of support, design researchers can then identify the needs of the users of support; derive requirements and provide support that is both useful and usable.

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“...while we cannot be taught to think, we do have to learn how to think well, especially how to acquire the general habit of reflecting.”

— John Dewey (1933, p.35)

Abstract

Human activities in the form of production and consumption have increased to an all-time high. In many cases, this increase has resulted in environmental problems such as waste and pollution that, in turn, affect our health and way of living. Societies have proposed different measures to address such environmental problems. These range from different waste treatment technologies to alternative business models, policy measures, and lifecycle thinking in the design of products, to mention but a few.

In this research, the focus is on supporting early design activities of what is often called the conceptual design stage with the objective to provide effective and resource-efficient offerings. The early design activities considered here are planning, analysis, and evaluation.

Design researchers have largely supported these three activities with a variety of methods and tools. However, previous research has shown that design support coming from academia has had a low uptake in industry. In this regard, the aim of this research is to propose not only useful but also usable support for design practitioners during the conceptual design stage.

This research is carried out in the manufacturing sector in Sweden, where selected companies expressed an interest in collaborating with academia to address more thoroughly effective and resource-efficient offerings. To better match company needs and research from academia, this research took a pragmatic and cross-disciplinary approach. This research approach, along with literature reviews, semi-structured interviews, workshops, and questionnaires, shows different ways in which support can be made more useful and usable. The main gap addressed here is that the knowledge and the related skills of the user of the support have not been sufficiently explored.

The results include requirements of the user of the support, proposed methods and tools derived from the requirements identified, and, most importantly, the knowledge and skills needed by the user of the support.

The main message of this research is that support could be expanded from methods and tools to include knowledge and skills needed by design practitioners, the users of support. The flow of support from academia to industry could also be reinforced in a two-way flow through a pragmatic and cross-disciplinary approach to first and foremost address design practitioners' needs.

Sammanfattning

Mänskliga aktiviteter i form av produktion och konsumtion har aldrig varit högre. Denna ökning över tid har i många fall lett till miljöproblem som avfall och föroreningar, vilka i sin tur påverkar vår hälsa och levnadssätt. För att möta dessa miljöproblem har olika åtgärder föreslagits, som tekniker för avfallshantering, alternativa affärsmodeller, policy och livscykeldesign, för att nämna några.

Fokus i forskningen som presenteras i denna avhandling är på tidiga designaktiviteter, vilka ofta kallas det konceptuella designstadiet och som syftar till att ta fram resurseffektiva erbjudanden. Detta steg behandlas här genom att närmare undersöka designaktiviteterna planering, analys och utvärdering.

Designforskare har till stor del stöttat dessa tre aktiviteter med en mängd olika metoder och verktyg. Emellertid visar tidigare forskning att designstöd från akademien har ett lågt upptag i industrin. Syftet med denna forskning är därför att föreslå ett användbart stöd som också är användarvänlig för utövare under det konceptuella designstadiet.

För att uppnå detta genomförs forskningen inom tillverkningssektorn i Sverige där deltagande företag uttryckt ett intresse av att samarbeta med akademien avseende resurseffektiva erbjudanden. För att bättre matcha företagets behov med forskning från akademien antas en pragmatisk och tvärvetenskaplig strategi. Denna strategi, tillsammans med litteraturöversikter, semistrukturerade intervjuer, workshops och enkäter visar hur stödet i det konceptuella designstadiet kan bli mer användbart och användarvänlig. Den huvudsakliga forskningsluckan som tas upp här är att kunskap och relaterade färdigheter hos användaren av stödet inte har undersökts tillräckligt.

Resultatet ger en beskrivning av kraven på de stöd som användaren behöver, föreslag på metoder och verktyg som baseras på de identifierade kraven och, viktigast av allt, den kunskap och de färdigheter som användaren av stödet behöver ha.

Huvudbudskapet är att stöd kan utvidgas från att omfatta metoder och verktyg till att även inkludera behovet av kunskap och färdigheter hos designutövare, det vill säga användarna av supporten. Stödet från den akademiska världen till industrin kan också förstärkas genom att bli ett tvåvägsflöde som med en pragmatisk och tvärvetenskaplig strategi först och främst adresserar användarens behov.

Acknowledgements

I first want to thank my main supervisor, Dr. Tomohiko Sakao, for giving me this great opportunity and for his continuous feedback and guidance in this process. Dr. Anne-Marie Tillman provided me with very useful input regarding environmental sustainability, and I thank her for the support provided as my secondary supervisor. I also want to thank Dr. Mattias Lindahl for his feedback and enthusiasm in carrying out the project with industrial partners. The companies that have participated in this research are also acknowledged for their support and time provided during visits, annual meetings, and constant emails.

I want to thank my colleagues from the Division of Environmental Technology and Management at Linköping University for providing an atmosphere for fruitful outcomes. I also wish to thank colleagues from other universities, especially Chalmers University of Technology in Sweden and the University of Tokyo in Japan, for their support in carrying out successful research. Moreover, my family has been of extreme importance in my achievements, and I consider them part of who I am, whom I admire the most, and who have been my role models in life; thank you, mom, dad and brother.

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Preface

About this work: This is the continuation of my previous work, published in February 2018 as a licentiate thesis. Now, as a compilation doctoral thesis, it emphasizes the pragmatic and cross-disciplinary approaches for carrying out design research when addressing real-world problems. This thesis describes activities early in the design process, namely, planning, analysis, and evaluation. The companies taking part in this research are part of the resource-efficient and effective solutions (REES) program Phase I, which ran between 2015 and 2019. Their selection and participation were based on their interest in improving the effectiveness and resource efficiency of their offerings.

Audience: This compilation thesis has as its main audience researchers of design in general and of the lifecycle approach to design in particular. Practitioners can also benefit from this research to improve their understanding of design theory, knowledge to carry out design with a lifecycle approach, and, more importantly, to benchmark their support used with some of the findings highlighted in the discussion section of the thesis. The wider audience, especially students in engineering design, product development, and environmental management, can use this thesis to increase their knowledge of design in general and about how manufacturing companies and academia are working together to address design support to tackle effective and resource-efficient offerings. This thesis can also serve as a reference if a student wishes to further develop knowledge to pursue a career related to the lifecycle approach to design.

Title: The title highlights the different components of this research. Support includes the possible means, aids, and measures that can be used to help design practitioners achieve their goals. The conceptual design stage may vary but in general starts with identifying a need or problem, continuing with the gathering of requirements, proposal of solutions, analysis and evaluation and final selection before entering a more detailed design stage. Effective and resource-efficient offerings, the aim; encompass a wide range of means that look for meeting customer needs while minimizing the impact on the environment and retaining resource value. Offerings include products, services, and systems.

List of appended papers and contributions

- Paper I** 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 *Designing Sustainable Technologies, Products and Policies* (pp. 381-389). Springer, Cham. doi: 10.1007/978-3-319-66981-6. In this conference paper, I was responsible for most of the writing (co-wrote the case study) as well as tables and figures.
- Paper II** Brambila-Macias, S.A. (2020). *Support used and further needs to realize effective and resource-efficient offerings: A comparison among large companies and small and medium enterprises*. Manuscript based on conference Paper 6 (see other related publications). I developed the paper and research questions with the support of my main supervisor. I analyzed the data and wrote all sections.
- Paper III** 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. doi: 10.1016/j.jclepro.2017.09.226. In this paper, I shared responsibility with my main supervisor in writing and producing the different tables and figures. I carried out the background literature review.
- Paper IV** Brambila-Macias, S. A., Sakao, T., & Kowalkowski, C. (2018). Bridging the gap between engineering design and marketing: insights for research and practice in product/service system design. *Design Science*, 4. doi: 10.1017/dsj.2018.3. I wrote most sections, 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.
- Paper V** Brambila-Macias, S.A., & Sakao, T. (2020). Effective Ecodesign Implementation with the Support of a Lifecycle Engineer. *Journal of Cleaner Production*, 279, 123520. doi: 10.1016/j.jclepro.2020.123520. I pointed out the need, the research gap and developed the concept of *lifecycle engineer*, carried out the literature review, interviews, transcription and coding. I wrote most sections in the paper.
- Paper VI** Matschewsky, J., Brambila-Macias, S.A., Neramballi, A. & Sakao, T. (2020). A method for the development and selection of design methods - investigating the design of resource-efficient offerings. Manuscript. I originated the idea, later developed with the first author and my main supervisor. I carried out part of the literature review, questionnaire and organized the workshop with practitioners.
- Paper VII** Willskytt, S., & Brambila-Macias, S. A. (2020). Design Guidelines Developed from Environmental Assessments: A Design Tool for Resource-Efficient Products. *Sustainability*, 12(12), 4953. doi: 10.3390/su12124953. In this paper I contacted the designer that helped in developing the tool, carried out early workshops. I co-developed the tool with the first author, also a PhD candidate, and wrote different paragraphs relevant to usability and usefulness.

Paper VIII Kimita, K., Brambila-Macias, S.A., Sakao, T., & Tillman, A.M. (2020). Failure Analysis Method for Enhancing Circularity through System Perspective. *Journal of Industrial Ecology*. doi: 10.1111/jiec.13069. I carried out the case study with the main author and wrote the case study section. I addressed comments from the reviewers about the severity of environmental aspects with support of my second supervisor Dr. Anne-Marie Tillman.

Other related publications

1. 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 (pp. 137-144). ISSN 1847-9073.
2. Brambila-Macias, S., Nilsson, S., Widgren, M., Lindahl, M., & Sakao, T. (2017). State of the Art of Design Methods for Resource Efficient and Effective Solutions: Report from “Product and Service Design Methods for REES” Project of Mistra REES program. LiU Press. ISRN: LIU-IEI-RR--17/00264—SE.
3. Brambila-Macias, S. A., Nilsson, S., Widgren, M., Lindahl, M., & Sakao, T. (2017). Support for Designing Resource Efficient and Effective Solutions: Current Use and Requirements by Swedish Industry: Report from “Product and Service Design Support for REES” Project of Mistra REES program. LiU Press. ISRN: LIU-IEI-RR--17/00281—SE.
4. Brambila-Macias, S. A. (2018). Early stages of designing resource-efficient offerings: An initial view of their analysis and evaluation (Vol. 1801). Linköping University Electronic Press. Licentiate thesis.
5. Brambila-Macias, S., Sakao, T., & Lindahl, M. (2018). Requirements for REES design support: A survey among large companies and SMEs. LiU Press. ISRN: LIU-IEI-RR--18/00304—SE.
6. Brambila-Macias, S. A., & Sakao, T. (2019). Analysis and evaluation in the early stages of designing resource efficient offerings: A comparison among large companies and small and medium enterprises. In *Proceedings of the Design Society: International Conference on Engineering Design* (Vol. 1, No. 1, pp. 3161-3170). Cambridge University Press. doi: 10.1017/dsi.2019.323.
7. Brambila-Macias, S.A., & Sakao, T. (2019). Methods and tools used in the Swedish manufacturing industry during the early stages of design. LiU Press. ISRN Number: LIU-IEI-RR--19/00308—SE.

Glossary of terms

Analysis	An activity that seeks the feasibility of the gathered requirements through for example modeling and simulation in an evolving design project which are used to make a proposal(s) or a conceptual solution(s) to reach a goal. (partly based on Sim & Duffy, 2003; Vallet et al., 2013).
Complexity	In general it is the state of having many parts and being difficult to understand or find an answer to (Cambridge Dictionary, 2020). In this research complexity occurs since the knowledge needed to realize effective and resource-efficient offerings resides in multiple disciplines (adapted from ElMaraghy, ElMaraghy, Tomiyama, & Monostori, 2012).
Conceptual design stage	The stage 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 research, the conceptual design stage is divided into the general activities of planning, analysis, and evaluation before a concept or proposal is produced as the output of the conceptual design stage.
Cross-Disciplinary research	A general term referring to the unspecified involvement of more than one discipline (Ciesielski, Aldrich, Marsit, Hiatt, & Williams, 2017).
Design practitioner	A professional that is actively engaged in the activities of design and development (adapted from Oxford Dictionary, 2020).
Design and development	<p>A set of processes that transforms requirements into specified characteristics or into the specification of a product, process, or system (ISO 14955-1:2017). In this thesis:</p> <ul style="list-style-type: none">• Designing (the process, the verb) is differentiated from design (the outcome, the noun) to emphasize the social process of designing with its multiple stakeholders, multiple objectives, and multiple iterations (based on Bucciarelli, 1988 and Vinck et al., 2003).• Early stages of designing can include planning and feasibility studies, among other activities, with the objective of determining the allocation of resources to fulfill a set of requirements and continue with the consecutive stages in the design process. In this thesis, the activities concerned are planning, analysis, and evaluation as part of the conceptual design stage (based on Vallet et al., 2013).

Ecodesign	The 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).
Eco-efficiency	The ratio between the created value or fulfilled function by the product system on the one side, and the resource use or impact that is caused on the other side (based on Hauschild, Kara, & Ropke, 2020).
Effective	To be successful in producing a desired or intended result (Oxford Dictionary, 2020).
Efficient	The ratio of an output to a corresponding input (ISO/TR 11065:1992).
Evaluation	An activity that sets a criteria which can be based in for example customers' preferences or expert judgement and used to decide on a proposal(s) or conceptual solution(s) to reach a goal. (partly based on Sim & Duffy, 2003; Vallet et al., 2013).
Interdisciplinary research	This is 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).
Knowledge	The understanding of the relevant causal mechanisms that generated the data and facts (Ciesielski, Aldrich, Marsit, Hiatt, & Williams, 2017).
Lifecycle approach	A systems-oriented approach for designing more ecologically and economically sustainable product systems that integrates environmental requirements into the earliest stages of design (Keoleian & Menerey, 1994).
Natural resources	This includes air, water, land, flora, and fauna (UNEP, 2010).
Offering	can be products, services, and/or systems (based on Isaksson, Larsson, & Öhrwall-Rönnbäck, 2009).
Planning	An activity that seeks to manage the uncertainty and complexity of an evolving design project through for example systematic gathering and updating of requirements and responsibilities for them to reach a goal. (partly based on Sim & Duffy, 2003; Vallet et al., 2013).
Pragmatism	A school of philosophy, dominant in the United States in the first quarter of the 20th century, based on the principle that the usefulness, workability, and practicality of ideas, policies, and proposals are the criteria of their merit. It stresses the priority of action over doctrine, of experience over fixed principles (Encyclopedia Britannica, 2020).
Resource efficiency	It 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, 2020).
Support	The possible means, aids, and measures that can be used to improve design. This includes strategies, methodologies, procedures, methods, techniques, software tools, guidelines, and information sources addressing one or more aspects of design (Blessing & Chakrabarti 2009).
Sustainability	The use of services and related products which respond to basic needs and bring a better quality of life while minimizing the use of natural resources and toxic materials as well as the emissions of waste and pollutants over the life cycle of the service or product so as not to jeopardize the needs of future generations (UNEP, 2010).
Transdisciplinary research	Research that transcends disciplines by employing a systemic view (Transdisciplinary 1) or collaboration between academic and non-academic partners to establish a common framework (Transdisciplinary 2) (see Sakao & Brambila-Macias, 2018).
Uncertainty	A situation in which something is not known, or something that is not known for certain (Cambridge Dictionary).
Usability	(1) Usability is the concept of whether the support provided is easy to use and understand and (2) the likelihood of implementation in practice. (Willskytt & Brambila-Macias, 2020).
Usefulness	(1) Usefulness is the concept of whether the support provided is informative and (2) whether it leads to the improved resource efficiency of a design concept (Willskytt & Brambila-Macias, 2020).

Selected acronyms

CE	Circular Economy
CFMEA	Circularity Failure Mode Effect Analysis
DfE	Design for Environment
DRM	Design Research Methodology
ISO	International Organization for Standardization
LCA	Lifecycle Assessment
MCDM	Multi-Criteria Decision Making
PSS	Product Service System
QFD	Quality Function Deployment
REDIG	Resource Efficient Design Guideline
TD	Transdisciplinary

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1 Introduction

This chapter introduces the motivation for the research as well as its framing. The chapter also provides the main objectives and research questions of the research. It then lists the appended publications and briefly shows how these addressed the research questions. Limitations of the research are also provided and a brief outline for each chapter is found at the end of this introductory section.

1.1 Motivation for the research

Design 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 and final solution (National Society of Professional Engineers, 2013). Much research in design has hence been dedicated to improving design by providing some type of support that includes strategies, methodologies, procedures, methods, techniques, software tools, guidelines, and information sources addressing one or more aspects of design (Blessing & Chakrabarti 2009).

However, there is **low uptake of academic design support in industry** (Tomiya et al., 2009). One of the main reasons for this low uptake could be a mismatch between the support provided by academics and how support is often used in industry. Wallace (2011) states that practicing designers consider many design methods to be too complex, inflexible and fail to match their working practices. This problem has been long debated and remains at the core of design research since its beginnings in the 1960s (Cross, 1993a). For example, Christopher Alexander, one of the most prominent proponents of design methods, was quoted in the 1970s as saying, “I have dissociated from the field”, since little about design methods offered anything useful (see Bayazit 2004, p. 21). 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.

Moreover, in the article *My method is better!*, Reich (2010) suggests that design practitioners already use some kind of support in their practice, and when confronted with a new one coming from academia, most design practitioners find it difficult to replace their favorite method. Reich (2010, p. 140) argues that justifying a new method is rather difficult since its successful transfer requires “not just throwing the method over the wall” but embedding it into the firms’ practices. Not addressing the problem of low uptake of support in industry could potentially turn into an identity crisis and challenge the *raison d’être* of design research. If this problem is not addressed, the consequences could go beyond design research. For example, when practitioners overlook support coming from academia, opportunities to address customer needs effectively and efficiently could be missed and ultimately affect business success. Hise et al. (1989) showed that product design activities have an effect on commercial success, and The National Research Council (1991) in the US stated that the consequences of better design practice, education, and research are shorter development time, lower costs, and a better match of products to customer needs.

Furthermore, several authors, for example, Manzini (2009), Rosen and Kishawy (2012) and De los Rios and Charnley (2017), have argued that design practitioners need to integrate new skills and knowledge in their practice to support the necessary system transformation towards a more sustainable future. This is necessary since manufacturing companies are now expected to contribute to sustainable development by implementing sustainable practices and reducing their environmental impact (Esmaeilian, Behdad, & Wang, 2016); not doing so will result in increased environmental degradation.

Additionally, in September 2015, the United Nations (UN) general assembly agreed and approved the 17 sustainable development goals (SDGs), which aim at balancing economic progress and protection of the environment (Leal Filho et al., 2019). The SDG goal number 12, sustainable consumption and production, states that *urgent* actions are needed to avoid over-extraction of resources and further degradation of environmental resources (UN, 2015).

1.2 Framing the research

This research is concerned with support for the early design activities, which is often called **the conceptual design stage** of the engineering design process. The early design activities of the conceptual design stage addressed here are those of planning, analysis, and evaluation later described in Section 2.4. The conceptual design stage is part of the larger innovation process (Roozenburg & Eekels, 1995) where creativity is important. However, innovation and creativity are not the focus of this research. Moreover, this research takes an **environmental perspective** in the conceptual design stage by integrating the concept of **lifecycle** to the design of products, services and systems (see Umeda et al., 2012).

Research in, for example, environmental management systems, green supply chain management, industrial ecology, and systems engineering overlaps with that presented here. This is acknowledged; however, the point of departure, scientific lens, and main field of research addressed here are engineering design with relevant integration of environmental science. This is what can be called a lifecycle approach to design, defined as a “systems-oriented approach for designing more ecologically and economically sustainable product systems that integrates environmental requirements into the earliest stages of design” (Keoleian & Menerey, 1994, p. 650). This definition implies that the scope of the sustainability addressed here is limited to environmental and economic sustainability¹. Although the nature of engineering is associated with societal values that impact design, social sustainability is not covered in this research.

Finally, in the first edition 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 a broader audience. Therefore, a pragmatic and cross-disciplinary approach is taken in this research to bridge knowledge across disciplines and more effectively collaborate with industry to support their needs during their design activities for effective and resource-efficient offerings. Effective means to be successful in producing a desired or intended result, and resource efficiency is defined as “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, 2020).

¹ Sustainability is a very broad field of research and not the focus of this compilation thesis. However, in the discussion chapter, the type of sustainability influencing this research is provided so the reader can better understand the view adopted in this research.

This research also has important assumptions to be clarified as part of framing the research. These **main assumptions** are as follows:

- The design of effective and resource-efficient offerings results in higher complexity and uncertainty in need of some type of *support* to be carried out efficiently and effectively.
- The *support* of early design activities carried out by design practitioners can lead to effective and resource-efficient offerings.

1.3 Aim, objectives, and research questions

The overarching question to address the problem of low uptake of support in industry coming from academia is this: **How can design researchers better support industry?** This question guides the aim of this research, which is to **propose useful and usable support during the conceptual design stage of effective and resource-efficient offerings by using a pragmatic paradigm and a cross-disciplinary research approach**. This is in the context of manufacturing companies.

The objectives and research questions to achieve the aim are as follows:

1. The first objective is to understand what support is used in industry. This objective is formulated in the first research question:
 - **RQ1: What support do manufacturing companies use for designing effective and resource-efficient offerings in the conceptual design stage?**

The design research methodology (DRM) is followed in this research as guidance for scientific design research (explained in Chapter 3). This methodology suggests looking at the as-is state before embarking into further research activities. This is central to design in order to transform an undesired situation into a desirable one, which requires exploring the situation or problem before proposing any solution(s) (see Blessing & Chakrabarti, 2009).

2. The second objective is to propose design support that can be useful and usable for practitioners, the second research question is:
 - **RQ2: How could manufacturing companies be better supported for designing effective and resource-efficient offerings in the conceptual design stage?**

Frost (1999) had previously pointed out that design researchers need to address design practitioners' needs in manufacturing companies with a pragmatic paradigm. This is because practitioners already have defined routines and ways of working that make the introduction of new support difficult to be accepted (see Reich, 2010). This research, hence, uses a pragmatic paradigm to design research (explained in Chapter 3). Moreover, the DRM methodology used here as guidance advocates evaluating the support provided from academics, which can be done by evaluating the usefulness and usability of the support (see Blessing and Chakrabarti, 2009 in Chapter 2).

3. The third and final objective is to examine the knowledge needed by manufacturing companies. The third researcher question is then:

- **RQ3: What knowledge is needed for manufacturing companies to design effective and resource-efficient offerings in the conceptual design stage?**

Researchers have pointed out that support coming from academia is often not used in industry due to several reasons, which can be summarized as follows: methods tend to be too complex, abstract, and theoretical; too much effort is needed to implement them; the immediate benefit is not perceived; methods do not fit the needs of designers and their working practices; and little or no training and support are provided by companies (Wallace, 2011). Moreover, Cantamessa (2003) previously stated that in design research, the development of new support is often done in isolation from industrial needs, the current state of the art, and implementation issues. Hence, previous literature is considered, and a cross-disciplinary approach is adopted (explained in Chapter 3. Methodology) to formulate the right problem and find the right solution.

The research questions can be best described in the following Figure 1 adapted from Wallace (2011) where industrial companies are in one domain and academic ones in another one, the problem of low uptake of support pushes for research to bridge these two.

Figure 1 Research questions addressed (adapted from Wallace, 2011)².

1.4 Limitations of the research

There are two important limitations in this research. These are addressed here so the reader is aware of them throughout this compilation thesis.

- Not only production of companies but also sustainable consumption from users and their behavior have become increasingly important to address (see Lofthouse & Prendeville, 2018). The behavior of users is only partially addressed in Paper VII.
- The collection of companies that participated in this research are based in Sweden. Although the results are generalizable, specific circumstances of for example, culture, and leadership were not covered in this research.

² When a table or figure is *adapted from* another source some modifications have been made from the original one, when it is *based on*, it attempts to represent it as accurately as possible as in the original source. *Inspired by* is when the source provided an idea for a figure or table.

1.5 Appended papers and research questions addressed

Table 1 below briefly shows how each paper answers the research questions. Although, some overlaps exist in the papers regarding the answers to the research questions, the papers’ major contributions to the research questions are marked with an X. The arrows represent how the output from Papers I and II influenced Papers III to V, which in turn influenced Papers VI to VII, completing the cycle to answer the overarching question of how can design researchers better support industry? (see the cycle in Figure 1.)

Table 1 Relation between research questions and appended papers

Appended papers	RQ1	RQ2	RQ3	Answers the research question in the following manner:
Paper I	X			It shows how a case company developed and made use of a checklist tool, a type of support for the planning and evaluation activities in the conceptual design stage.
Paper II	X			It shows the support used by eight manufacturing companies as well as their needs to realize effective and resource-efficient offerings.
Paper III			X	It clarifies transdisciplinary research and highlights that knowledge can be found across disciplines.
Paper IV			X	It is an example of the benefits from interdisciplinary research. What engineering design can learn from marketing.
Paper V			X	An example of TD type I and a knowledge holder in the form of a lifecycle engineer.
Paper VI		X		Requirements for support based on literature review, a questionnaire and workshops with academics and practitioners.
Paper VII		X		A tool developed with the requirements of the support from Paper VI, and addressing lifecycle thinking as found in Paper V. It is tested in a case company and evaluated for its usefulness and usability.
Paper VIII		X		A method proposed for circularity addressing systems thinking, a skill in demand as suggested in Paper V.

Papers I and II address RQ1. These papers describe the support used (see Papers I and II) and further needs in industry for the planning, analysis, and evaluation (see Paper II) of their offerings.

Papers VI, VII, and VIII address RQ2. These papers address the requirements of the support (Paper VI) and a proposed tool (Paper VII) that takes into account the requirements of the support from Paper VI. It also evaluates the support in terms of usefulness and usability. Paper VIII is a method for circularity that is an example of systems thinking as needed by manufacturing companies, which was identified in Paper V.

Papers III, IV, and V address RQ3. The main argument in these papers is that useful knowledge to address the lack of uptake of support could benefit from cross-disciplinary research, which includes inter and transdisciplinary research. Paper III clarifies what is meant by transdisciplinarity (TD) Types I and II. Paper IV finds insights into what engineering design can learn from marketing for researchers and practitioners and is an example of interdisciplinary research. Paper V exemplifies TD Type I with the proposal of a knowledge holder.

1.6 Structure of the thesis

The structure of the thesis flows from the introduction presented in Chapter 1 to the results described in Chapter 4, all of which are taken into account in the discussion (Chapter 5) followed by the final conclusion (Chapter 6), as depicted in Figure 2. First, Chapter 2 presents the theoretical background for this research, namely, theory in design and literature regarding the lifecycle approach to design. It then presents what is meant by the early stages of design and the design activities of planning, analysis, and evaluation. Next, Chapter 3 describes the paradigm underpinning this research as well as the cross-disciplinary research approach taken. It also presents the methods and data analysis used throughout the research. Following that, Chapter 4 summarizes the results from the appended papers and highlights the major findings. Chapter 5 then provides a discussion on the different aspects raised in Chapters 1 to 4. Finally, Chapter 6 provides the answers to the research questions and whether the aim of the research was met. Future research for the support offered for design practice is also proposed in this final section.

Figure 2 Structure of the thesis

2 Theoretical background

This chapter focuses on giving the reader a panoramic view of the relevant theories and state of the art of the literature. It first presents the theories in design research at large, then the literature relevant for the lifecycle approach to design, and lastly support for the early design activities of planning, analysis, and evaluation in the conceptual design stage.

2.1 Theories in design research at large

It has been stated that to design is human, which suggests that we are all designers. It is then not surprising that design can be understood in different ways depending on its applications. In *An Anthology of Theories and Models of Design: Philosophy, Approaches and Empirical Explorations*, Chakrabarti and Blessing (2014) review major theories and models in design. The publication provides discussions on what a theory or model is, the criteria for something to be categorized as a theory or model, and how theories and models can be validated. While there are no clear answers to the questions addressed in their publication, different views are described. One of the views on theory presented here, as understood by Eder (2014, p. 200), is that “theory should describe and provide a foundation for explaining and predicting the behavior of the concept or (natural or artificial, process, or tangible) object, as subject”. Eder continues: “The theory should answer the questions of why, when, where, how (with what means), who (for whom and by whom), with sufficient precision”.

This definition of theory provided by Eder (2014) seems to be a mature one often seen in other fields of research, for example, the natural sciences. The differences and similarities between science and design have long been debated. For instance, the central difference has been suggested to be that science is concerned with understanding the universal properties of what exists, while design is concerned with conceiving what does not yet exist (see Galle & Kroes, 2014). For some authors, science and design show striking similarities. For example, Braha and Maimon (1997) suggest several similarities between natural sciences and engineering design. For them, natural sciences originate with observations about the natural world, while engineering design originates in the requirements of human adaptation in the environment. Both science and engineering design are iterative, the former with reformulations of explanations due to new observations and the latter with artifact proposals that respond to new requirements. In *Science and design: Identical twins?*, Galle and Kroes (2014, p. 228) reach a conclusion to their metaphorical question that “science and design are relatives, perhaps even siblings; they often enjoy each other's company, but they are hardly twins, and certainly not identical twins”. The authors point out the following differences:

- Aim: science describes or studies the world, while design changes the world.
- Subject matter: both science and design share the natural and artificial world, but design proposes artificial things based on results from science.
- Products: both science and design produce symbolic artifacts but differ in their theories. Theories in science are cognitive-descriptive, but in design are practical-descriptive.
- Methodology: science and design differ in the criteria for the evaluation of solutions to problems. Truth is paramount in evaluating a scientific theory, but it is non-sensical to discuss the truth of an artefact proposal. Trade-offs play a central role in design evaluation, which is not the case in science.

Most research and education in engineering design, however, seem to have followed scientific design, what Stempfle and Badke-Schaub (2002) have called the normative strain of design research, or what Dorst (1997) called a rational paradigm as opposed to the design practice or empirical paradigm. This normative strain seems to be followed by authors that have attempted to provide a unifying theory of design (see Love, 2002), and it is also in line with Herbert Simon (1969) and his *Sciences of the Artificial*. For example, Theory of Technical Systems (Hubka & Eder, 2012), General Design Theory (Hatchuel, Le Masson, Reich, & Subrahmanian, 2018), FBS framework (Gero, 1990), and Axiomatic Design Theory (Suh, 1998) are some examples.

Major contributions to the design process in this normative strain of theory include Pugh's Total Design (1991), The Association of German Engineering's (VDI) guidelines (VDI, 1993), which are similar to Pahl & Beitz's phases in design, mechanical design (Ullman, 1992), and the Taguchi method (Taguchi & Phadke, 1989) for quality and robust design (see a review in Adams, 2015 in Chapter 2). Some of the advantages and disadvantages of these systematic processes (models of design) 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 models can be easily followed by practitioners. The disadvantages, however, are that most of these models 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), or overlooking daily work and economic and time constraints (Ehrlenspiel, 1999).

Criticism against the normative strain of design is found in what Stempfle and Badke-Schaub (2002) call *the empirical strain*. The empirical strain depicts the normative design methodology as rigid and not reflecting of practice. Hence, other design researchers seem to follow a more pragmatic and reflective theory of design. This view of design theory could be best explained by Vermaas (2014, p.9), who stated that "Design theory is an attempt to systematically bind together the knowledge we have of experiences of design practices". This view of theory is the one adopted in this research. This theory of design seems to follow what Donald Schön (1984) called *reflection in action*. In this view of design theory, authors such as Buchanan (1992) and the concept of wicked problems and research addressing knowledge needs (see Ahmed & Wallace, 2004) and ethnographic studies (see Bucciarelli, 1988) seem to be more descriptive of design practices in industry.

These different strains of design (normative vs empirical) are not necessarily clear cut, and some overlaps exist (see Kimbell, 2011). For the purpose of clarity, these are presented as different theoretical approaches in Table 2. Experts in design are expected to have different understandings or views of what design is and how different theories are used.

Table 2 Theoretical framework: theoretical approaches and their use in this thesis (inspired by Kimbell, 2011)

Theoretical approaches (strain)	Design theories	Object of study (main question)	Purpose	Keywords	Key literature	Used in this research
The cognitive approach (normative)	FBS framework	The mind (how do designers think?)	To solve design problems in an efficient and effective way	Cognition	Gero (1990)	To derive the activities of planning, analysis, and evaluation
	Bounded rationality			Thinking process	Simon (1969)	
The research and education approach (normative)	DRM,	The process (how to study the design process?)	Design through representation of the different parts of the design process	Teaching	Blessing & Chakrabarti (2009)	To find guidance in carrying out research in design
	Structured methodology			Learning	Dym et al. (2005)	
				Mechanical process		
The managerial approach (empirical)	Wicked problems	The management of the design process in a firm (how to better manage the design process?)	To tame wicked problems	Design thinking	Buchanan (1992)	To realize that offerings are characterized by high complexity and uncertainty that need to be managed and not solved
				Design management	Boland & Collopy (2004)	
The reflective practice approach (empirical)	Reflective practice	Design activities (how can design activities be better supported?)	To provide useful and usable support for efficient and effective offerings	Reflection	Schön (1982)	To reflect on usefulness and usability when designing support
	Pragmatic design			Experience	Bucciarelli (1988)	
				Usefulness		
				Relevance		

Note: This is a non-scientific and non-exhaustive table (own author's view of relevant design theories and how they were used in this research, as shown in the gray color column).

In regard to sustainability, Lang et al. (2012) suggest that sustainability challenges require new ways of knowledge production and decision-making. Since problem solving from a design perspective and in the context of sustainability have been described as complex, ill-structured, or even wicked and in need of cooperation across disciplines (Wahl & Baxter, 2008), this research takes a pragmatic and cross-disciplinary approach to design. This is because a pragmatic approach aims “for [] knowledge that is appreciated for being useful in action” (Goldkuhl, 2012 p. 144).

2.2 Review of the lifecycle approach to designing

The design literature offers different traces for the connection between design and environment as a distinctive practice. Madge (1997), for example, traces back the connection between design and ecology to the environmental movement of the 1960s and 1970s. Keoleian and Menerey (1994) point at Asimow’s work (1962), when the author developed a framework for a lifecycle approach to design that included production, distribution, consumption, and recovery or disposal. For their part, Ceschin and Gaziulusoy (2019) suggest that a response from the engineering design field to resource limitations, material production, and the impact on the environment can be traced back to Buckminster Fuller’s (1969) teachings and the concept of *Spaceship Earth*. This concept highlighted the physical limitations of our planet. In later years, Victor Papanek’s book *Design for the Real World: Human Ecology and Social Change* (1984) seems to have been a catalyst for changes in the design profession. Papanek criticized the design profession for encouraging consumption to the detriment of the environment and society.

Moreover, in the early 1990s, a wide range of design for X approaches to implement environmental and other considerations into design and development was proposed. For example, design for environment (DfE), usually used as synonymous with Ecodesign, is often found in engineering fields such as mechanical engineering (see Ashley, 1993) and a wide range of DfXs addressing specific considerations related to the environment exist. For example, design for recycling (DfR) (Kriwet, Zussman, & Seliger, 1995), design for disassembly (Harjula, Rapoza, Knight, & Boothroyd, 1996), and design for remanufacturing (Ijomah, McMahon, Hammond, & Newman, 2007), among many more (see the review by Benabdellah, Bouhaddou, Benghabrit, & Benghabrit, 2019).

Most relevant to this research are Ecodesign, PSS design and circular design at the micro level (single company or product) as examples of what can be called a lifecycle approach to product designing where efficiency and effectiveness are often addressed.

Efficiency is usually cited as doing things right while effectiveness as doing the right thing (see Abukhader, 2008). Efficiency tends to be more related to measuring a process and effectiveness to the outcome of a process (see Lundholm, Lieder & Rumpel, 2012). The term eco-efficiency is usually addressed as an indicator (Caiado, de Freitas Dias, Mattos, Quelhas, & Leal Filho, 2017), which can be generally described as a ratio, for example: eco-efficiency equals economic value divided by environmental impact (Mickwitz, Melanen, Rosenström, & Seppälä, 2006).

2.2.1 Review of Ecodesign

Ceschin and Gaziulusoy (2016, pp. 121-122) 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”. Since its early beginnings in the early 1990s, Ecodesign³ has seen multiple contributions and it is recognized by some researchers as a well-developed field of research (Hollander et al., 2017). Pigosso et al. (2015) 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). Other similar terms include design for lifecycle, and green design (Kutz, 2015). According to ISO:14006 (2011, p. 2) 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”. This is in line with what The Design for Environment Decision Support (DEEDS) project concluded which was that Ecodesign needs to be integrated in the early stages of design, after a certain point then it becomes very difficult to alter the product features critical for environmental performance (Bhamra, 2004).

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 support (methods and tools). Reasons for this have been attributed to a lack of knowledge about the tools, a lack of specialized staff (see Paper V as an example of a specialist called a lifecycle engineer), unsuitable company size, and a lack of cooperation between divisions in a company, among others (ibid). Poulikodou 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.

Examples in literature on how to provide more effective support are offered by Lindahl (2005, 2006) who suggests that methods and tools should, for example, be easy to understand; that is, they should be intuitive, logical, and easy to communicate, among other important characteristics. Additionally, Lofthouse (2006) suggests that successful tools possess three characteristics: information, guidance, and education (see the tool proposed in Paper VII, as it follows many of these suggestions).

Criticism in Ecodesign questioned its foundations. For example, Hollander et al. (2017) suggested that Ecodesign principles, strategies and methods are based on the here and now. Hollander et al. (2017) considered Ecodesign a relative approach which is more suitable for the linear economy (make-use-waste). 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. As design researchers and practitioners in manufacturing companies began to realize that the effects of increases in production were insufficient for remaining competitive (see Beuren et al., 2013) a shift towards offering value through a combination of products and services began to emerge

³ The word ecodesign is capitalized when referring to the area in the literature. When referring to ecodesign as a design activity, it is not capitalized.

(see Morelli, 2003). This shift hence emphasized the effectiveness of an offering in terms of meeting customer needs while considering the natural environment (see Goedkoop et al., 1999).

2.2.2 Review of PSS design

Several literature reviews have discussed PSS design. 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, literature reviews by Beuren et al., 2013 and Annarelli et al., 2016). Definitions about PSS abound in the literature, with the earliest usually attributed to Goedkoop et al. (1999) and Mont (2002). For example, PSS was defined by Mont as follows: “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” (Mont, 2002, p.2). However, Annarelli et al. (2016) suggested that environmental sustainability had been losing its importance in PSS, and Vezzoli et al. (2015) have stressed the sustainability aspect of PSS in what they call the Sustainable Product Service System or S.PSS (see Vezzoli et al., 2018, p. 41) providing an alternative definition: “an offer model providing an integrated mix of products and services that are together able to fulfil a particular customer demand (to deliver a “unit of satisfaction”), based on innovative interactions between the stakeholders of the value production system (satisfaction system), where the ownership of the product/s and/or its lifecycle responsibilities remain by the provider/s, so that the economic interest of the providers continuously seek new environmentally and/or socioethically beneficial solutions”.

Contributions on how to design a PSS are often prescriptive and tested in case companies. For instance, Morelli (2003) proposed a design process and a case study of a telecenter. In addition, Morelli (2006) provided more specific tools for designing a PSS through interaction maps, IDEF0 modelling and service blueprinting. Tukker and Tischner (2006a) review several design methods, tools and projects aimed at providing clearer guidelines into how to design a PSS. Moreover, a network called the *Sustainable Product Development Network*, or SusProNet, carried out different projects in this area between 1997 and 2002. The findings of the SusProNet suggested that much of the theory of PSSs was not well linked to business literature⁴ (Tukker & Tischner, 2006b). More recently, it has been established that in PSS design, understanding value creation and its capture throughout the lifecycle is an important prerequisite (Bertoni, Bertoni, & Isaksson, 2013) (for different perspectives on value and costs see Paper IV).

⁴ A large body of literature in PSS focuses on business models, not covered here. For more information see for example Lüdeke-Freund et al. (2019).

2.2.3 Review of circular design

Ghisellini et al. (2016) describe three different levels of Circular Economy (CE) applications: the micro (single company or product), the meso (eco-industrial systems, industrial ecology) and the macro (cities, regions, or countries) levels. The authors suggest that implementation at the micro level remains limited. Kirchherr et al. (2018) suggest that barriers to successful implementation include cultural, regulatory, market, and technological issues. Kirchherr et al. (2018) argue that circular design while not a major impediment for CE is at the core of the technological issues.

Moreover, it is common to see R-measures, e.g., re-manufacture, re-cycle to implement CE (Reike, Vermeulen, & Witjes, 2018). In circular design, considered here as CE at the micro level, many guidelines and frameworks present a prioritized list or hierarchy of these R-measures, for example, the reuse, repair, remanufacture, and recycle of products (ibid). However, as suggested in appended Paper VII, a ranking list of R-measures may not be useful for design practitioners since these hierarchies do not consider for example low collection rates in recycling or losses in remanufacturing, hence providing a ranking is less useful for design practitioners. Instead, the characteristics of the products (see paper VII) and their systems (see Paper VIII) should be at the forefront of the design endeavor.

Furthermore, a large amount of CE indicators addressing performance e.g., efficiency and effectiveness has been proposed in literature. Saidani et al. (2019) review several of the available indicators and give as examples those that are applicable to the micro level as Circular Economy Indicator Prototype (CEIP), product-level circularity metric (PCM) and material circularity indicator (MCI). For their part Kravchenko et al. (2019, p. 14) suggest that “sustainability-related indicators can support designers in assessing the potential sustainability performance of the product prior to its production and subsequent utilization”. Nevertheless, the practical use of indicators for design practitioners remains a challenge (Saidani, Yannou, Leroy, & Cluzel, 2017) which could be due to conflicting objectives among actors and their activities when closing material flows (Coenen, van Der Heijden, & van Riel, 2018).

2.3 Theories in early stages of designing

Designing rather than design is a preferred term here to emphasize the process happening in an organization which often involves multiple stakeholders, objectives, and iterations. In this view not only designers but also other actors such as customers, project managers, quality managers and suppliers, among others, are involved (see Paper II). This view is similar to that of authors that propose a more descriptive view of what happens out in the field (see Bucciarelli, 1988 and Vinck et al., 2003). It is more a social process (see Minnemann & Harrison, 1998) than only a cognitive one (see Gero, 1990).

In this research, what is relevant are the design activities happening in manufacturing companies, large and small. These design activities often occur throughout what is called product design and development. The early stages or phases of design as understood in product design and development are those that comprise planning and concept development, in some cases referred to as Phase 0 and Phase 1, respectively (see Dieter & Schmidt, 2013; Ulrich & Eppinger, 2012) or simply the conceptual design stage. This stage can in turn include activities such as planning, problem formulation or feasibility studies before reaching a decision and continue with a more detailed stage (George & Linda, 2013). In Table 3, some examples of the normative view of design are provided based on Ogat and Kremer (2004, p.12). What can be considered the early design stages are highlighted in gray color.

Table 3 Early stages of designing (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 the 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		Production ramp-up	

Note: Early design stages according to different authors are highlighted in gray color

The conceptual design stage is considered the most important in terms of costs and environmental impacts. It has been estimated that 70 to 80% of product costs are determined during this phase (Ullman, 1992). Lewis et al. (2001) stated that most of the environmental impact of a product is *locked-in* at the conceptual design stage. Yet during this initial stage little is known about the final product, especially when the product to be designed is new to the design practitioners. This is usually referred to as *the design paradox* (see Lindahl & Sundin, 2013) depicted in the Figure 3 below.

Figure 3 The design paradox (based on Lindahl & Sundin, 2013)

Moreover, the conceptual design stage is part of what Roozenburg & Eekels (1995) called the phases of the product development and innovation phases. This normative representation of the design process is provided so the reader can easily locate the focus of this research. Highlighted in Figure 4 is product designing, of which the conceptual design stage is a part.

Figure 4 Product development and innovation phases (based on Roozenburg & Eekels, 1995)

Note: Focus of this research highlighted in gray color

The product designing phase can be also composed of different stages. Figure 5 below is adapted from Pahl and Beitz (1996). It highlights in gray color the conceptual design stage and also the derived design activities used in this research: planning, analysis and evaluation.

Figure 5 Product designing (adapted from Pahl & Beitz, 1996)

Note: Focus of this research highlighted in gray color. Although a concept is an output in the conceptual design stage, the focus in this thesis is for supporting the activities before the final output.

Since the conceptual design stage (see Figure 5 above) can include different stages or activities (see Table 3), relevant to this research are more generalizable activities originally proposed by Stempfle & Badke-Schaub (2002) derived from systematic processes (normative view) and from cognition (see Figure 6 below) these activities are: planning, analysis and evaluation.

Figure 6 Design activities of planning, analysis, and evaluation (adapted from Stempfle & Badke-Schaub, 2002)

Note: Focus of this research highlighted in gray color.

Figure 6 shows how design activities are derived from normative and cognitive models to provide more generic design activities. These activities are explained next.

2.4 Support in the early stages of designing

The activities of planning, analysis, and evaluation may overlap and several iterations among them could occur before a decision is made (see Santos, Gazelle, Rocha, & Tavares, 2012). The Figure 7 below represents how planning, analysis and evaluation may occur in practice. In a study of design practice Hales (1987) showed that some design activities overlap which is why this overlap is represented below.

Figure 7 Representation of planning, analysis, and evaluation in practice (inspired by Santos et al., 2012)

The following descriptions of planning, analysis and evaluation are partly based on Sim & Duffy's (2003) ontology of *generic* design activities, Stempfle and Badke-Schaub (2012), Vallet et al. (2013) and Paper II which point at some companies, usually SMEs, not following a systematic process as proposed in normative-academic models but still doing planning, analysis and evaluation early when designing.

- **Planning** is an activity that seeks to manage the uncertainty and complexity of an evolving design project through for example systematic gathering and updating of requirements and responsibilities for them to reach a goal.
- **Analysis** is an activity that seeks the feasibility of the gathered requirements through for example modeling and simulation in an evolving design project which are used to make a proposal(s) or a conceptual solution(s) to reach a goal.
- **Evaluation** is an activity that sets a criteria which can be based in for example customers' preferences or expert judgement and used to decide on a proposal(s) or conceptual solution(s) to reach a goal.

A proposal is a presentation of ideas containing adequate description of the purpose, needs analysis, and identification of the problem with conclusions and references (Ostrofsky, 1977). For the conceptual design, different interpretations exist (Keinonen & Takala, 2010), similarities among these interpretations appear to be that a conceptual design represents the function(s) of a device, or object-system, its structure and behavior (see Gero, 1990 and Keuneke, 1991).

Early design activities of offerings that are both effective and more resource efficient can be more complex and uncertain than offerings that do not consider, for example, the closing of material flows. This could be the case since multiple actors and conflicting objectives need to be considered for closing materials flows (Coenen, van Der Heijden, & van Riel, 2018). Hence, support can help companies navigate throughout this complexity and uncertainty. The early stages of design seem to benefit most from qualitative and easy-to-use tools. This could be partially explained by the lack of information, risk, uncertainty, and subjectivity found during the early stages (Fitzgerald, Herrmann, Sandborn, Schmidt, & Gogoll, 2007).

In the context of design, a method can be described as a systematic procedure to reach a specific goal (Pahl & Beitz, 1996) and a tool as an implement that facilitates the use of a method or an aid to using a method (Norell, 1996). Reviews by researchers in the field of lifecycle design point at an ever-growing number of methods (Pigosso, McAloone, & Rozenfeld, 2015; Rossi, Germani, & Zamagni, 2016). In the field of Ecodesign, Bovea and Pérez-Belis (2012) provided a taxonomy of methods and tools for integrating environmental requirements in the design process. The authors concluded that the implementation of methods and tools is scarce and that most of them are not applied due to their complexity, the time required to apply them, and the lack of environmental knowledge in companies. Bovea and Pérez-Belis (2012) also proposed three key factors for support: early integration of environmental aspects into the product design process, lifecycle thinking, and multi-criteria approach.

In PSS design, Vasantha et al. (2012) reviewed 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) provided a generic design methodology for a PSS to increase practicality and provide guidelines for designers and developers. Recent literature reviews suggest that research in PSS as a field of study has been increasing in recent years and expanding across disciplines such as strategy, marketing, sustainability, service science, business management, design, engineering, and information systems (Li, Kumar, Claes, & Found, 2020), making it more difficult to classify PSS design support in a meaningful way. In circular design at the micro level, support classification is often provided based on DfX strategies (see Moreno et al., 2016) and performance indicators (see Kristensen & Mosgaard, 2020).

In this research, the classification of support is provided according to the derived activities of planning, analysis, and evaluation. Although these may overlap, a brief overview of common support is provided here for each of these activities. The support described below is based on reports (see Other related publications section, 3 and 7).

2.4.1 Support for planning

Quality function deployment (QFD) as presented by Akao (1990) is a commonly used by many companies when integrating customer requirements with product design (Sivasamy, Arumugam, Devadasan, Murugesh, & Thilak, 2016). Its variant for the environment, QFDE, proposes adding environmental aspects to a list of requirements (Masui, Sakao, Kobayashi, & Inaba, 2003). Additionally, some support can serve the purpose of idea generation or to inform (see Bahmra & Lofthouse, 2016). Design guidelines, matrices and checklists can be used for these purposes. Examples include: the ten golden rules, later renamed principles by Luttrupp & Lagerstedt (2006), the materials, energy and toxicity (MET) matrix which is an abridged version of life cycle assessment (LCA), useful at the beginning of the design process (Brezet & Van Hemel, 1997) and the ECODESIGN checklist proposed by Wimmer (1999).

2.4.2 Support for analysis

Wrisberg et al. (2002) provide a review of analytical environmental support for environmental design and management. Among these supports are cost benefit analysis (CBA), cost effectiveness analysis (CEA), material flow analysis (MFA), life cycle assessment (LCA), environmental risk assessment (ERA) and material input per service unit (MIPS). Life Cycle Costing (LCC) is also among support to address resource efficiency. LCC was initially created in the mid-1960s to assist the US department of defense with procurement of military equipment before it was used to analyze environmental performance in for example buildings and other fields (Gluch & Baumann, 2004). Other types of analytical support often seen in literature include Failure Mode Effect Analysis (FMEA) and a plethora of hybrid methods found in the field of multi-criteria decision making (MCDM) (see Fattahi & Khalilzadeh, 2018).

2.4.3 Support for evaluation

Support for this activity can include environmental benchmarking methods (see Boks & Stevels, 2003) or for example, Saaty's (2004) analytical hierarchy process (AHP) and analytical network process (ANP) for ranking and selection, respectively. These types of support can be used when selecting among "green" alternatives (see Govindan, Rajendran, Sarkis & Murugesan, 2015). Georgiadis et al. (2013) conduct an extensive literature review that highlight the use of AHP for selecting among alternatives especially in the early phases of design. The authors also highlight the importance of systems engineering and the technique for order of preference by similarity to ideal solution (TOPSIS) as useful for selecting among different technologies. Ilgin et al. (2015) review several methods in the field of MCDM suggesting that many methods are used for evaluation and design. Apart from these methods mentioned earlier, those that consider a limited number of alternatives and discrete preference ratings are: DEMATEL, ELECTRE, PROMETHEE, multi attribute utility theory, VIKOR and MACBETH among others (see a review in Velasquez & Hester, 2013).

2.4.4 Main research gap in the literature

The main research gap identified is that design researchers have mainly focused on supporting the design activities with methods and tools without explicitly addressing the knowledge of the user of the support, as shown in Paper V. Knowledge defined here as the understanding of the relevant causal mechanisms that generated the data and facts (Ciesielski, Aldrich, Marsit, Hiatt, & Williams, 2017) of the user of the support has been less researched. Paper III clarifies knowledge production through cross-disciplinary approaches, Paper IV shows the benefits of using interdisciplinary research to transfer knowledge across disciplines and Paper V specifically addresses the issue of knowledge and user of the support simultaneously. This knowledge is also accompanied by skills in demand as presented in Papers II and V. This main gap is illustrated in Figure 8. used to represent the gap in literature to include support that addresses knowledge and skills of the user of the support.

Figure 8 Main research gap in the literature (own author’s interpretation)

3 Methodology

This chapter first describes the paradigm chosen for this research, the use of cross-disciplinary research and the design research methodology (DRM). Additionally, the methods for collecting data and its analysis are presented.

3.1 Paradigm underpinning this research

Weingart (2010) suggests that early philosophers, such as Plato and Aristotle, attempted to study human knowledge to understand how it could be organized and best acquired. Since then, the acquisition and production of knowledge have gone through many changes. For example, Van Doren (1991) mentions that the scientific revolution of the XVII century and the birth of modern science is usually attributed to Francis Bacon and the scientific method. A change of paradigm, where dogma and beliefs were replaced by rationality, marked the scientific revolution. The enlightenment in the XVIII century 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 perspective (normative strain), or as reflective in practice (empirical strain). Since this research addresses real-world problems, cross-disciplinary, pragmatic, and reflexive approaches are recommended (Bawden & Allenby, 2017; Martens, 2006). Table 4 below shows different paradigms adapted from Wahyuni (2012), where pragmatism is highlighted in gray as the one used in this research.

Table 4 Research paradigms (adapted from Wahyuni, 2012)

Fundamental believes	Major research paradigms (related paradigms)			
	Positivism (Naïve Realism) (Rationalism) (Empiricism)	Postpositivism (Critical Realism)	Interpretivism (Constructivism)	Pragmatism
Main representatives ⁵	Francis Bacon (1561–1626) René Descartes (1596–1650) Auguste Comte (1798–1857)	Karl Popper (1902–1994) Thomas Kuhn (1922–1996)	Paul Feyerabend (1924–1994) Ludwig Wittgenstein (1889–1951)	Charles Sanders Peirce (1839–1914) William James (1842–1910) John Dewey (1859–1952)
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 and 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

Note: Paradigm adopted in this research is highlighted in gray color.

According to Robson (2011), the central idea of pragmatism is that the usefulness of concepts consists in their practical implications and that truth is defined as *what works*. **Hence, in pragmatism, a researcher will use whatever philosophical or methodological approach that best fits the research problem at hand (ibid).**

⁵ Based on different reading passages in Hjørland (2005), Hay (2008), Weingart (2010), Chalmers (2013) and Capps (2019).

Dorst and Dijkhuis (1995) previously contrasted two main paradigms to describe design activities: on the one hand, the rational one highlights the importance of the design process, and on the other, the reflective one in which the focus is on the design practitioner and how to frame a problem rather than following a logical process. According to the authors, the unit of *doing design* in the rational paradigm is the design concept that will be evaluated, whereas in the reflective one, the unit of *doing design* is an action, and design practitioners evaluate their own actions in structuring and solving a problem similar to pragmatism.

The pragmatic approach has also been highlighted by Dickson and Stolterman (2016, p. 4059), especially when addressing the usability of design methods; these authors suggest that “a substantial part of method development efforts, especially those in academia, are not carried out as user-centered design processes even though they are done by those who commonly advocate such an approach”. Schønheyder and Nordby (2018) also highlight how practice-generated methods are developed through pragmatic and user-centered approaches.

Moreover, Melles (2008) points out that pragmatism has permeated several disciplines of design. For example, urban planning, architecture, and information technology are the disciplines with the most impact, and a renewed interest in pragmatism is presented by Dixon (2020), who advocates for pragmatism as the philosophy for design research moving forward. Dixon (2002) suggests that under this paradigm, design research includes design practice and that it, too, can provide valid knowledge.

Finally, in pragmatism, abductive reasoning appears to be key in producing new ideas (Koskela, Paavola, & Kroll, 2018). According to Rylander (2012), abduction is the logic of *what might be*, as opposed to other forms of logic e.g., induction and deduction, which are analytical approaches to determine *what is*. In this research the type of reasoning followed could be argued to be abductive. This since the research addresses a real-world problem to which previous theories are considered. New or surprising observations then attempt to extend the theories used (see Spens & Kovács, 2006).

3.2 Design research methodology (DRM) as guidance for scientific research

Criticism to design research as lacking scientific rigor saw the effort from design researchers to enable a more systematic research of design. In this respect, the design research methodology, or DRM, proposed by Blessing and Chakrabarti (2009), was used here as guidance on how to carry out research that follows a more rigorous process. Other design research methodologies acknowledged by Blessing and Chakrabarti (2009) are soft systems methodology (SSM) and the one proposed by Duffy and Andreasen (1995) with similarities to DRM. The DRM is presented in the figure below.

Figure 9 DRM (based on Blessing & Chakrabarti, 2009)

It is important to acknowledge that the DRM has some limitations; for example, project concerns such as the time needed to carry out a project, costs of a project, and access to practitioners may hinder following the different parts of the methodology. Hence, Blessing and Chakrabarti (2009) suggest that DRM can be followed in its entirety or used in a flexible manner where some of its different steps are considered.

Therefore, DRM was used here as guidance on how research in design is to be carried out in a more systematic manner. For example, Research Question 1 provides an as-is state, Descriptive Study I (DS-I) of the support used in industry, which was addressed in Papers I and II. Paper V follows Descriptive Study II (DS-II) in the DRM for the five constructs of method, organizational context, performance, user, and knowledge to classify the literature. In Paper VI, DRM was also used for the development and evaluation (using QFD) of support. Paper VII provides measures of the proposed support in terms of usefulness and usability, as suggested in the DRM.

3.3 Cross-disciplinary research

Cross-disciplinary research is an all-encompassing term that includes multi, inter, and transdisciplinary approaches. Multidisciplinary research refers to research that includes more than one discipline and where each discipline makes a separate contribution (see Paper III). 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. Finally, Transdisciplinary Research (TD) Type I is one that transcends disciplines by employing a systemic view, for example, new curricula for a new discipline, and TD Type II is one that employs a comprehensive framework, often represented by working with non-academic partners (see Ciesielski et al., 2017 and Sakao and Brambila-Macias, 2018).

An example of contrasting disciplines is provided by Aagaard-Hansen (2007), who states that all disciplines are grounded in theoretical foundations and paradigms. Examples of contrasting disciplines are biomedicine and anthropology. Aagaard-Hansen mentions that differences among these two disciplines range from research ethics to terminology and power balance. Aagaard-Hansen (2007) provides some suggestions to overcome barriers in cross-disciplinary research; some of these are that researchers should have some knowledge about the other participating disciplines and the use of facilitators to assist in necessary discussions so that definitions are addressed and clarified from the start. Aagaard-Hansen (2007) suggests considering contextual factors such as evaluation procedures, funding agencies, and publication traditions for overcoming barriers.

Another example is provided by Grimheden and Hanson (2005), who describe the evolution of mechatronics in different stages. These stages suggest that mechatronics went from a collection of loose disciplines without interactions among each other to a stage where mechatronics was considered multidisciplinary and where students combined disciplines to broaden their knowledge. According to Grimheden and Hanson (2005), the next stages in the evolution of mechatronics included cross-disciplinary courses, for example, giving courses in electrical engineering to mechanical engineers (example of interdisciplinarity). The next stages are represented by new curricula representing this cross-disciplinary approach to finally establishing mechatronics departments achieving a thematic identity (example of TD Type I).

Similarly, in design, struggles among design disciplines have been encountered. Advocates for a unifying theory of design such as Love (2002) suggest that the lack of a unified body of knowledge and theory about designing and designs is due to differences in philosophical foundations, for example, theory belonging to a single domain of practice, not acknowledging epistemological and ontological issues, disagreement in definitions of core concepts and terminology, and poor integration of theories from other bodies of knowledge.

To overcome the barriers of cross-disciplinary research in design, Love (2002) suggests reducing ambiguity and inconsistency in core concepts as well as providing epistemologically and ontologically foundations for theory-making. In design, Cross (1993b) and Galle (2008) have made efforts to disentangle and clarify differences and overlaps of concepts such as design science, the science of design, and design research to what it seems is to provide a more coherent and unifying theory of design. In this research, rather than looking for a unifying theory of design, different disciplines provide a rich field that can be exploited to address the problem of low uptake of academic design support in industry. Finally, the responses in the last decades to human impact on the environment seem to favor a cross-disciplinary approach. Harding et al. (2009) presented an evolution of the responses to

environmental problems, as shown in Table 5, which shows how problems have been addressed in different decades.

Table 5 Responses in the last decades to human impact on the environment (based on 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	Through regulation Cumulative Regional impacts	Through regulation Cumulative and strategic Ecosystem to global (depending on the issue)
	Short temporal scale	Longer temporal scale	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

Note: Approach most representative of this research highlighted in gray color.

3.4 Methods

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 applicable 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 are the literature review, the case study method, semi-structured interviews, questionnaires, and workshops.

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. A narrative literature review was used in Paper III, a systematic one was used in Paper IV, and a combination of narrative and systematic was used in Paper V.

Case study: Case study research is defined by Yin (2009, p. 16) as “an empirical inquiry that investigates a contemporary phenomenon (the ‘case’) in depth and within its real-world context”. The case study 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 a strong bias from the researcher, not knowing when to stop the case study, and the validity of the findings (Voss et al., 2002). Paper I presents a single case study that describes a checklist tool at a manufacturer. Paper II uses multiple cases to describe the support used by manufacturing companies and their needs. Paper VII and VIII also make use of a single case study to propose a tool and a method, respectively.

Semi-structured 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. A difficulty when carrying out an interview is that there is a need to develop some *rapport* (DiCicco-Bloom & Crabtree, 2006), that is, a 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. Semi-structured interviews were carried out in Papers II and V.

Questionnaires: Robson (2011) suggests that questionnaires are widely used as social research methods. Questionnaires can be administered after participants have been involved in an activity such as an experiment, seminar, or workshop. In the case of Paper VI, a questionnaire was used for selected practitioners to answer questions related to the necessary characteristics of methods for resource efficiency derived from literature. Similarly, a questionnaire was used in Paper VII after a design practitioner made use of the proposed tool.

Structured workshops: Krueger (2014) is often cited for the focus group method of data collection. Here, the preferred term is the structured workshop since the number of participants in, for example, Paper VII, was only one practitioner using the proposed tool. In this structured workshop, presentations, guidance in using the tool, and final discussion were the structure followed. For Paper VI, a similar approach was followed by practitioners and academics.

3.5 Data analysis

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 analytical method, which relies on a series of steps to formulate and analyze different themes (Fereday & Muir-Cochrane, 2006), was used in Papers IV and V. In Paper IV, a thematic analysis was used to see how engineering design and marketing were using each other’s insights. In Paper V, thematic analysis was used to form codes and later categories for the transcribed semi-structured interviews.

Documentation: Guidelines by Ashby (2000) and Rangachari and Mierson (1995) show how to write and what to look for in a journal article, some of which are presented below.

Table 6 Some guidelines for analyzing journal papers (adapted from 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 allowed for a more structured analysis of literature to find relevant gaps (see Papers IV and V).

Descriptive statistics: According to Fisher and Marshall (2009) descriptive statistics are used to organize, present and analyze data. Basic descriptive analysis was carried out to analyze questionnaires administered for Paper VI to derive nominal measurements from participants and ordinal measurements for the characteristics of the support important to practitioners.

4 Results

This section summarizes the appended papers. It shows how each paper answers to the research questions. It also describes how the papers are interlinked.

4.1 Research question 1

The first research question was **RQ1 What support do manufacturing companies use for designing effective and resource efficient offerings in the conceptual design stage?**

The answers for this question are found in Papers I and II. **Paper I**, entitled *Development of an environmental evaluation tool in the transport sector and its impact on decision-making in the early stages of design*, was written with practitioners at a manufacturing company. It shows how the company in the transport sector developed a checklist tool for planning and evaluation. The case study shows the working process of the case company to establish a useful and usable checklist. 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 secure 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, often found in quality management for continuous improvement. In the case company, this was done by identifying an organizational need, while also taking into account other factors such as core company values and external requirements like ISO 14001.

Paper II, entitled *Support used and further needs to realize effective and resource-efficient offerings: A comparison among large companies and small and medium enterprises*, compares support used and further needs between three large companies and five SMEs. Commonalities among SMEs and large companies include decisions made by strategic or managerial boards, the use of mock-ups, and project management skills, among others. Differences show that large companies follow a formal product development process, while SMEs usually do not have a formal process. Differences also include larger companies having available staff for specific tasks, while SMEs rely on key personnel to carry out multiple tasks. Also, the business owners in small companies are directly involved in many of the businesses' operations, which is not the case for large companies. Uncertainties seem to be addressed more formally in large companies, whereas smaller ones tend to go for gut feeling or rely heavily on key personnel, for instance, the owner of the company. The needs from companies point to that support for communication and lifecycle thinking is needed. Support that already addresses analysis and evaluation in, for example, the field of multi-criteria decision making (MCDM) was not mentioned during the interviews.

Conclusion: There is a wide variety of support companies make use of during the design activities of planning, analysis, and evaluation. Some of the support for planning is for example QFD. Support for analysis include product testing, mock-ups, lab tests, LCAs and economic calculations, among others. Support for evaluation is for example A3 reports and matrix-based evaluations. Support in the form of MCDM was not found to make part of the design practitioners' type of support. A major finding is that communication and lifecycle thinking are in demand and that interviewees did not ask for a specific MCDM method. An emphasis on the knowledge and skills required to design with a lifecycle approach could possibly provide more usefulness and usability to design practitioners.

4.2 Research question 2

The second research question was **RQ2 How could manufacturing companies be better supported for designing effective and resource efficient offerings in the conceptual design stage?**

The answers to this question are found in Papers VI, VII, and VIII. **Paper VI**, entitled *A method for the development and selection of design methods - Investigating the design of resource-efficient offerings*, is an initial attempt to support method selection and development with a focus on resource-efficient offerings. The paper is based on the semi-structured interviews from Paper II. Later, questionnaires, and structured workshops with industry practitioners and academic method designers were carried out to identify critical requirements and characteristics for method development and method selection. The method supports reflexive, rigorous, and impactful design research practice. Therefore, manufacturing companies could be better supported if design researchers first gather requirements of the user of the support to be provided, and design researchers can also use successful methods, such as QFD, to better capture requirements as presented in Paper VI.

Paper VII, *Design Guidelines Developed from Environmental Assessments: A Design Tool for Resource-Efficient Products*, which describes a tool called REDIG, was developed based on learnings from several lifecycle assessments and provides design recommendations for the improved resource efficiency of products based on product characteristics. The tool found inspiration in the ten golden principles by Luttrup and Brohammer (2014). The tool was developed using the requirements from Paper VI and was then tested in a design case, where its usefulness and usability (as suggested in DRM) were evaluated using a comparative lifecycle assessment and a questionnaire. The evaluation showed that the tool was useful in that it provided useful information and design suggestions that lead to improved resource efficiency. The tool was considered usable as it could be implemented in design practice. The proposed tool (REDIG) also described possible trade-offs of different measures. This paper is an example of lifecycle thinking, which is a need in demand found in Paper II and V.

Paper VIII, *Failure Analysis Method for Enhancing Circularity through System Perspective*, extends failure mode and effect analysis (FMEA), with a proposed method called circular FMEA (CFMEA). The study makes use of a single case study of a small manufacturer aiming to increase circularity with its products on the market. The proposed method was found to be useful in the early stages of design and was found to be effective in identifying failure modes where effects are largely given to or received from other failures and then developing effective countermeasures by addressing their root causes. The paper explains that additional support might be needed for CFMEA to be more useful for larger companies and to increase its usability. This paper is an example of systems thinking, a skill found to be in demand from Paper V.

Conclusion: Manufacturing companies could be better supported by design researchers first deriving requirements for the support. These requirements fulfill the needs that point at knowledge and skills, as described in Papers V and VI. These needs were partially covered in Papers VII and VIII with a method and a tool, respectively, and which were based on previous, well-accepted support e.g., guidelines and FMEA. Although an effort was made to secure usefulness and usability that were qualitatively evaluated, their actual implementation in practice could be addressed in future research.

4.3 Research question 3

The third research question was **What knowledge is needed for manufacturing companies to design effective and resource-efficient offerings in the conceptual design stage?**

This question is answered in Papers III, IV and V. **Paper III** is entitled *Do we share an understanding of transdisciplinarity in environmental sustainability research?*, and is a letter to the editor of the Journal of Cleaner Production (JCLP) questioning if there is a shared understanding of one of its aims “an international, transdisciplinary journal focusing on cleaner production, environmental, and sustainability research and practice”. In this letter, the objective was to raise the question of what is meant by the term transdisciplinary. A literature review carried out for this purpose showed that what is meant by transdisciplinarity is still contested. This letter to the editor then proposed two ways to understand it. Transdisciplinary type I (TD I) is a more systemic discipline. Transdisciplinary type II (TD II), or what is known as Mode 2 knowledge production, is participatory research between academia and non-academic partners to address real-world problems. The letter calls for more discussion around this research approach. The importance of transdisciplinary research and its clarification are explained to overcome barriers to integration, communication among researchers, and the comparison and evaluation of results, which are key for knowledge production. Thus, Paper III was crucial when addressing support, or in other words, how cross-disciplinary research can provide benefits for supporting manufacturing companies. Looking at the knowledge found in different disciplines, it expanded the support in the form of methods and tools to knowledge and skills, as shown in Papers IV and V.

Paper IV, *Bridging the gap between engineering design and marketing: Insights for research and practice in product/service system design*, addresses what engineering design can learn from marketing in the form of insights at three levels: Level 1, when one discipline cites the opposite discipline; Level 2, when one discipline uses an insight found in the opposite discipline; and Level 3, when a model, framework, method, or tool is directly used in the opposite discipline.

Paper IV also provides a research agenda. Insights identified in the literature 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, while 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. Finally, in the services theme, it is argued that engineering design can rely on the vast knowledge in marketing on how to offer services successfully. These themes also provided opportunities to further advance the understanding of how to design PSSs effectively and efficiently.

Paper V, *Effective Ecodesign Implementation with the Support of a Lifecycle Engineer*, is based on design theory (DRM) and cross-disciplinary research (TD I) and proposed a knowledge holder, called a lifecycle engineer, with specific knowledge and skills that can support a team or organization in implementing ecodesign more effectively. The results of this paper show that for effective ecodesign implementation knowledge needed includes lifecycle analysis, materials and their selection, energy efficiency, legislation, and management; while relevant skills include communication, systems and lifecycle thinking.

The proposal of a lifecycle engineer, according to most practitioners, was found to be useful. The advantages of a lifecycle engineer include having more focus on ecodesign and the availability of information and staff to drive changes. Caveats included clear financial benefits for the company, especially for smaller ones, and enough tasks for full-time employment. The knowledge holder also has the potential to support implementation in other fields of research, for example, design for sustainability and the circular economy, to better transfer knowledge from academia to industry and vice versa.

Conclusion: There is a need to clarify cross-disciplinary research to fully exploit the potential benefits to address the low uptake of support in industry. Paper III shows that transdisciplinarity is poorly understood and clarifies relevant approaches with the aim to overcome barriers in, for example, the communication and evaluation of results across disciplines. Paper IV shows the benefits of interdisciplinarity with proposed insights, and Paper V proposes a knowledge holder, an example of TD I. Paper V states that the knowledge needed for ecodesign implementation includes lifecycle analysis, materials and their selection, energy efficiency, legislation, and management; relevant skills include communication, systems and lifecycle thinking.

5 Discussion

This chapter provides a discussion on the different sections of this thesis: from how the paradigm chosen impacted the overall research to the validity and reliability of the research. It then positions the type of sustainability in this research. Later in the chapter, a discussion of the major findings is provided as well as the possible contributions made in the scientific and practical domains.

5.1 Paradigm chosen for the research

The paradigm chosen for the research methodology was that of pragmatism. It is important to discuss how this paradigm impacted the overall methodology. Here, it is argued that taking into consideration pragmatism reveals that design researchers can be considered designers of support. This then poses the question, as in engineering design, of what the needs and requirements are of the user of the support and how these can be efficiently and effectively fulfilled. This is depicted in Figure 10.

Figure 10 Academics as designers of the support (own author’s interpretation)

The impact of pragmatism in design research then shaped the problem and the possible solutions to it. This was later reflected in the research questions. For example, in RQ1, the support used by design practitioners in manufacturing companies and their needs were addressed and answered in Papers I and II.

Additionally, cross-disciplinary research served the purpose of looking at the knowledge found in different disciplines in the academic domain that could address the needs identified for the users of the support.

The pragmatic paradigm, cross-disciplinary research, and the DRM provided the needed guidance to design support as if it were a product: from identifying a need to gathering the requirements (Paper VI) and involving other disciplines (Paper III) to find a possible solution for the low uptake of design support.

The consequence of applying a pragmatic approach as opposed to, for example, a positivist one, is that in positivism, experiments and theory verification are more common and could potentially remain in the domain of academic institutions, while in pragmatism, mixed methods and real-world practice are at the forefront of the research endeavor (see Mackenzie and Knipe, 2006), hence influencing the problem and possible solutions.

Therefore, a strong emphasis on needs and requirements is seen throughout the appended papers. Examples of these are found in Paper VI, which uses a well-known support method (QFD) for requirements. Paper VII provides a tool inspired by the ten golden principles by Luttrup and Brohammer (2014) that was developed from requirements in Paper VI, involving a designer (the user of the support), and then evaluating the support in its usefulness and usability.

5.2 Validity and reliability of the research

Validity and reliability are measures of research often seen in quantitative approaches, where hypothesis testing is common (Creswell & Creswell, 2017). While there are different views on how to best assess qualitative research (Rolfe, 2006), it is common to refer to the *quality of research* in qualitative studies, which can be attained by what Sandelowski (1993) calls *trustworthiness*. This trustworthiness is then further divided into credibility, dependability, transferability, and confirmability (Guba, 1981) to ensure rigor.

Credibility can be achieved with triangulation, among other strategies in qualitative research (see Guba, 1981). Triangulation requires cross-checking data and interpretations to reduce error (see Patton, 2014). In Papers II and V, this triangulation is most evident as data collection methods and analysis were cross-checked with other researchers and with practitioners to make sure that there was agreement with what was said in the interviews, workshops, or what was found in the literature.

Dependability can be achieved by what Bryman (2016) suggests as the auditing approach. This approach relies on the openness of data and information for external scrutiny. In this research, Papers IV, V, and VII made use of extensive appendices to reveal the data and its analysis. It also provided evidence to support the statements made. For example, in Papers IV and V, how each paper was categorized was made transparent.

Transferability is an assessment of the potential of the results to be transferred to other socio-cultural settings (Kuper, Lingard, & Levinson, 2008). The review of the literature in all papers took into account research papers from other sectors and countries; therefore, the data from the literature was the input to research in the Swedish context. While the results are presented to be transferable to other sectors and countries, this research was carried out in its entirety in the Swedish manufacturing sector. This limitation of the research results is acknowledged in this thesis and, for example, in Paper V.

Confirmability refers to obtaining direct and repeated affirmations (Morse, 1994); in other words, feedback is necessary for this category assessment of qualitative research. In this research, reports, transcriptions, and meeting notes were sent to participants to confirm if what was written accurately represented their input. Examples are found in a series of reports (see section Other related publications, numbers 3,5 and 7), which were later used for Papers II, VI, and VII.

5.3 Sustainability in this research

In Chapter 1, it was suggested that sustainability, although not the focus of the research, would still be briefly discussed for the reader to understand the view taken here of sustainability (see a discussion of other environmental concepts in Brambila-Macias, 2018).

The lifecycle approach to design, either in the form of Ecodesign, PSS design, or circular design, has the commonality of potentially transforming natural resources into offerings while avoiding, preventing, or reducing negative environmental impacts in an economically feasible manner. This is a more company-focused view of resources, something which can be called an eco-modernist view (Grunwald, 2018). In this view, sustainability needs to make business sense. Hence, sustainability in this research is closer to the definition of sustainable consumption and production (SCP), part of the Sustainable Development Goals (SDGs), defined as “The use of services and related products which respond to basic needs and bring a better quality of life while minimizing the use of natural resources and toxic materials as well as the emissions of waste and pollutants over the life cycle of the service or product so as not to jeopardize the needs of future generations” (UNEP, 2010 p.12).

Akenji and Begtsson (2014) make a case for SCP to be at the core of the SDGs, stating that unsustainable patterns of consumption and production have been proven to be the primary cause of environmental deterioration. Moreover, the United Nations’ 10-Year Framework for Sustainable Consumption and Production Patterns (10YFP) adopted in 2012 recognizes the need to change the way societies produce and consume (UNEP, 2010).

As with other terms, SCP can be interpreted in different manners. For example, Geels et al. (2015) propose three different SCP positions: reformist, revolutionary, and reconfiguration. The table below shows the positions of Geels et al. (2015) on scale and type of change, view of production, and view of consumption. The perspective that was taken in this research is most accurately represented by the reconfiguration interpretation.

Table 7 Sustainable consumption and production’s interpretations (based on Geels et al., 2015)

	Reformist	Revolutionary	Reconfiguration
Scale and type of change	Change in technical products and purchase behavior (encouraging consumers to buy green products through market incentives and information).	Overhaul of economic and sociocultural deep structures.	Transitions in socio-technical systems and practices.
View of production	Focus on firms, “green” products, eco-efficient production processes, and “greening” of supply chains.	Critique of capitalism, growth, and GDP obsession – pleas for “new economics”, grassroots initiatives, decentralized production, services, sharing economy, de-growth.	Focus on firms and industries, technological regimes, routines, capabilities, mindsets.
View of consumption	Focus on individual consumers as buyers and shoppers. – Positive view of consumption: consumer sovereignty, free choice, expression of preferences.	Focus on consumerism and materialism. Negative view of consumption: alienation, commodification as a threat to social order, over-consumption – pleas for frugality, sufficiency, and a focus on well-being over affluence.	Focus on practices and daily life, embedded in routines, habits, rules.

Note: Representative interpretation in this research is highlighted in gray.

According to Allen and Shonnard (2012), engineering design decisions are embedded in different layers. These layers can, for example, include an overall layer of social structure, followed by infrastructure, products, and finally, components. Similarly, Lukman et al. (2016) present a pyramid with different levels to visualize how different concepts relevant to SCP can be understood. Therefore, while this research can be considered to focus on the micro level (company or component), its impact can potentially go beyond this level to more meso (eco-industrial systems, industrial ecology) and macro (cities, regions, or countries) levels and support 1) a transition in socio-technical systems and practices, 2) change regimes, routines, capabilities, and mindsets, and 3) routines, habits, and rules by extending design research to also address knowledge and skills of the users of the support.

5.4 Discussion of concepts

In Section 2.2, it was suggested that there seems to have been a progression from the concept of eco-efficiency of products to highlighting more of their eco-effectiveness throughout the lifecycle. However, these concepts appear to be continuously debated with regard to their differences and similarities without clear conclusions (Bergmann, Günther, & Kara, 2017; Hauschild et al., 2020).

Aoe (2007) discussed the relation between Ecodesign and eco-efficiency. Aoe (2007) suggested that eco-efficiency is an indicator of Ecodesign. Eco-efficiency as an indicator had previously relied on for example Factor X as proposed by the Wuppertal Institute and the method Material Input per Service unit (MIPS). Factor 10 was defined to improve resource productivity and Factor 4 as doubling wealth and halving resource use as a form of dematerialization (see Ehrenfeld, 2005).

Discussion on types of eco-efficiency have also been suggested. For example, Hupples and Ishikawa (2005) proposed four different types of eco-efficiency as a bridge to better understanding the terminology. These types are presented in Table 8.

Table 8 Four basic types of eco-efficiency (based on Hupples & Ishikawa, 2005)

	Product or production focus	Environmental improvement focus
Economy divided by environment	production value per unit of environmental impact or <i>environmental productivity</i>	cost per unit of environmental improvement or <i>environmental improvement cost</i>
Environment divided by economy	environmental impact per unit of production value, or <i>environmental intensity</i>	environmental improvement per unit of cost, or <i>environmental cost effectiveness</i>

From the Table 8 above, it can be seen that for some authors effectiveness has been a part of eco-efficiency i.e., cost effectiveness. In this regard, Plouffe et al. (2011, p. 573) look at the economic benefits of Ecodesign where cost-effectiveness is addressed; the authors argue that “most important aspects to consider when getting involved in an ecodesign project is to focus on increased functionality of the product and to seek environmental and economic improvement on as many lifecycle stages as possible.” Those critical of eco-efficiency suggested that this concept was insufficient to reduce environmental impacts (Seiler-Hausmann, Liedtke, & von Weizsäcker, 2004) as gains in efficiency may be *eaten away* by increased consumption (Reijnders, 1998).

An answer to this criticism seems to be found in PSS which can potentially decouple economic value from material and energy consumption (see Ceschin & Gaziulusoy, 2016). In PSS design *satisfaction*, the effect, appears to be often highlighted (see the definition of S.PSS by Vezzoli, 2015) to evaluate customer satisfaction of PSS design (Kimita, Shimomura, & Arai, 2009).

In contrast to eco-efficiency, eco-effectiveness questions if resources are being used in an environmentally appropriate manner (Wang & Côté, 2011). This concept, attributed to McDonough & Braungart (2001) proposes using natural resources in a regenerative rather than depletive manner. Eco-efficiency and eco-effectiveness have been previously pointed out as complementary rather than replacing each other, and with the potential to act against rebound effects (Abukhader, 2008). According to Niero et al. (2017) the combination of these two concepts can address the challenges of designing circular systems. Moreno et al. (2016) suggest that research in CE has focused primarily on the development of new business models, without providing better guidance for designers on how to implement these new business models (see appended Paper VII as an example of design guidelines aimed at design practitioners).

Additionally eco-effectiveness seems to have also highly influenced the concept of CE (Korhonen, Honkasalo, & Seppälä, 2018) to address the technical and biological cycles of products and services (see Moreno et al. 2016). It seems that for some authors PSS and circular design are an evolution from previous concepts such ecological design and Ecodesign (see for example Ceschin & Gaziulusoy, 2016 and McAloone & Pigosso, 2017). The similarities across these approaches could be argued to be the lifecycle approach since it influences Ecodesign, PSS design and circular design. When the PSS design community has forgotten the sustainable aspects (see Annarelli et al., 2016 and S.PSS by Vezzoli, 2018), academics seem to remind the benefits of this lifecycle approach (see Sundin 2009).

The lifecycle of a product-service is composed of different stages (not to be confused with sales over time as seen in Marketing). These lifecycle stages usually include resource extraction, materials production, component production, product manufacturing, use, and end of use (EoU) before the end of life (EoL) when a product is incinerated, landfilled, or stored. A possible representation of the differences between eco-efficient, effective, and eco-effective is presented below in Figure 11 to provide a clearer picture of the differences among these concepts.

Figure 11 Possible interpretations of eco-efficient, effective, and eco-effective (own author's interpretation inspired by Sundin, 2009)

Note: This is a non-scientific figure, practitioners and academics will have different interpretations. This figure can be used for discussion of the differences and similarities between concepts.

Figure 11 shows eco-efficiency as a concept aiming at optimizing a process. The concept aims at optimizing the ratio between inputs and outputs to for example minimize emissions to the environment. Effectiveness focuses on the result (the outcome) of an offering between a provider and a customer or user, which can happen between several actors, for example between a materials production provider and a component production customer (see example 1) or a product manufacturer and a user (see example 2, usually seen in PSS literature). The case for eco-effectiveness could be rather to look at using resources, e.g., materials, in an effective manner to retain their value by for example closing material flows. The combination of eco-efficiency, effective offerings and eco-effectiveness has the potential to achieve absolute decoupling, indeed effective and resource-efficient offerings.

5.5 Discussion of the findings

The findings are here compared to previous literature to show to the reader how these make contributions at the scientific and practical domains.

5.5.1 Scientific

While the benefits of cross-disciplinary research to deal with complex and real-world problems and produce new knowledge has been stated (see Ciesielski, Aldrich, Marsit, Hiatt, & Williams, 2017), the understanding and differences between different approaches and especially TD seem to lack clarity (Sakao & Brambila-Macias, 2018).

The main contribution can be seen with the use of cross disciplinary research approaches e.g., TD I and II. These research approaches integrate disciplines (TD I) and non-academic actors (TD II) respectively for a better picture of the problem at hand and its possible solutions, this is the contribution of Paper III. The examples of using cross-disciplinary research are specifically highlighted in Papers I, IV and V. Paper I is an example of how a manufacturing company developed a checklist tool, and how this can help other practitioners and researchers hence TD type II; Paper IV is an example of interdisciplinarity, e.g., what engineering design can learn from marketing and Paper V is an example of TD type I, when specialized knowledge is formed from other disciplines. These cross-disciplinary research approaches have been suggested as having little impact in research in the past (Hadron et al., 2008), not been well understood (Stock & Burton, 2011), and researchers facing problems to find common ground (Ely et al., 2020). This may result in lack of full exploitation (see Paper IV) and overlook potential benefits. This research provides more clarity into what cross-disciplinary approaches mean for design, its benefits and possibly impact to society, for example the introduction of a specialist, a knowledge holder, called a lifecycle engineer (Paper V) which could be addressed by educational institutions and industry to co-develop a more specific body of knowledge.

The findings in Paper V for ecodesign implementation are summarized here. First the literature shows that Ecodesign has been addressed taking into account one or several of the following constructs:

- (1) Method: a predefined description that supports achieving a specific goal
- (2) Organizational context: organizational aspects such as origin and history, ownership and control, size, charter, technology, location, and dependence on other organizations that affect the implementation of an artifact.
- (3) Performance: an assessment of an intentional action.
- (4) Knowledge: understanding of the relevant causal mechanisms that generated the data and facts.
- (5) User: a person who uses an artifact.

Additionally, the knowledge needed for ecodesign implementation includes lifecycle analysis, materials and their selection, energy efficiency, legislation, and management. The relevant skills include communication, systems and lifecycle thinking.

Wallace (2011) suggested that knowledge transfer remains a challenge and most literature in the lifecycle approach to design also shows that there is often a lack of expertise from staff (see Dekoninck et al., 2016 and Rousseaux et al., 2017 for Ecodesign). In Paper IV, it was shown that the interlinkages between engineering design and marketing are low. This finding contributes to PSS since its design is more complex than designing only physical products, since the bundle of products and services needs

to be designed in unison (Morelli 2003) and calls for more interdisciplinarity have been made (see Boehm & Thomas, 2013).

Therefore, the main scientific contribution is best represented by RQ3 that addresses **knowledge needed**. In Paper V the knowledge and the user of the support were addressed in combination. Literature in Ecodesign points out that lack of knowledge from staff as one of the main barriers to successful implementation (see Poulikodou et al., 2014 and Rousseaux et al., 2017). In PSS design, similar concerns have been suggested. For example, offering products and services in combination presents challenges for design practitioners of how to handle data and information. Hence PSSs proponents have made calls to increase and better transfer knowledge to design practitioners so they can realize the design of PSSs (see Vezzoli et al., 2018). In circular design, the use of performance indicators by practitioners remains a challenge (see Saidani et al., 2017) which could potentially be attributed to lack of addressing knowledge needs by the user of the support or conflicting objectives among different actors. This is an important finding that points at design researchers possibly needing **to refocus their support to also include knowledge and skills of the user of the support**. This knowledge could be packaged in the form of insights as in Paper IV or as proposing a new specialist as in Paper V to address both knowledge and skills. Similar research has been proposed in for example information systems (see Goldkuhl, 2012) where pragmatism is a paradigm often used and which Dixon (2020) has proposed as the way forward for design research.

5.5.2 Practical

Pragmatism as a research paradigm makes clearer that a design researcher is also a designer of support. This has several benefits. The first one is that a researcher can place himself or herself in a similar position that design practitioners face: A need from which requirements are derived, to be met in an efficient and effective manner. The second one is that with pragmatism a researcher is more likely to not only consider usefulness but also usability of the support. Usefulness has already been highlighted by Lofthouse (2006) and usefulness and usability by Lindahl (2005). While most support seems to be useful, usability remains sparsely addressed in design research (see Dickson & Stolterman, 2016).

The third benefit of pragmatism is that it can address other needs from design practitioners, for example skills. Lifecycle thinking is a skill in demand found in Papers II, and V. Moreover, Paper V also points out at the need for systems thinking which is addressed in Paper VIII with the method CFMEA. Other needs identified point at better communication. In Paper II this was highlighted as a need for both large and small companies. Paper V also suggests that communication is an important skill to possess. With regards to support in the form of methods and tools, Paper II did not find specific demand for MCDM methods. The reason for this could be that companies often require the competence to carry out their design activities and not necessarily a method. This also points at design researchers needing to be clearer about the purpose of their method or tool and how it addresses the need of a company. Finally, the knowledge of the user of the support also needs to be addressed as shown in Paper V.

5.5.2.1 For design practitioners

The insights found in Paper IV, which address PSS design, are provided here for design practitioners. It focuses on what engineering design can learn from marketing. Insights from the marketing perspective about, for example, the customer or user could help engineering designers achieve more effective offerings.

- (1) Business orientation – Insight 1: *Strategic thinking when designing PSSs can contribute to the competitive advantage of the firm by expanding business opportunities and securing long-term profitability in uncertain business environments.* Engineering design usually looks for optimal use of resources and tries to follow a systematic process at the operational level. However, in marketing, this business orientation is more at the strategic level, which usually means a much longer-term view; this means to think, for example, how an offering can change over time, as this can contribute to the competitive advantage of the firm.
- (2) Collaboration – Insight 2: *Organizational configurations for a PSS can range from collaboration with individual customers and their suppliers to entire networks that can include competitors as part of providing solutions to the customer.*
- (3) Cost aspects – Insight 3: *When offering PSSs, hidden costs may arise in the form of resistance to change, re-training and investment when creating relational rather than transactional relationships.* If companies only focus on costs, they may overlook value for the customer, which is often highlighted in marketing hence hidden costs should be considered when moving from merely transactional to closer customer relations.
- (4) Flexibility – Insight 4: *In order to offer PSSs, the provider could adopt temporary teams during different stages of design and delivery and improve flexibility as needed by an external customer.* This insight shows that flexibility in engineering design focuses on modularity and customization, but in marketing, this refers to the organizational capabilities of a company and how it can be adjusted according to customer needs.
- (5) Performance Indicators – Insight 5: *Performance indicators for PSS offerings should cover both the efficiency and effectiveness to reflect the impact of the offering on firm value and customer value.* Engineering design usually refers to the indicator of efficiency to measure performance. In marketing, however, effectiveness is more often talked about. For example, engineers would take into account the reduction of materials and energy use, but in marketing, the focus will be on the effect that different offerings have on the firm's market value or its success in the market.
- (6) Requirements – Insight 6: *For a successful PSS offering, both customer and provider may need to make necessary adjustments to their tangible and intangible capabilities in order to specify, communicate and capture value.* In engineering, functional and technical requirements are often encountered, but in marketing, these go beyond tangible requirements. Marketing tries to understand the customer's needs and how they may change over time, which are more intangible.
- (7) Services – Insight 7: *Engineering design can rely on the marketing discipline for guidelines, frameworks, and tools on how to offer services successfully.* Engineering design can adopt guidelines, frameworks and tools found in marketing to successfully design and provide complex offerings.

6 Conclusion

This section presents the answers to research questions; whether the main aim at the beginning of the research was met or not and possible future research.

6.1 Answers to the research questions

RQ1 What support do manufacturing companies use for designing effective and resource efficient offerings in the conceptual design stage?

There is a multitude of support in the form of methods and tools that manufacturing companies make use of during the early design activities of planning, analysis, and evaluation. Some of the support is well known for example QFD and FMEA. Examples of support for planning are checklists (see Paper I) and *pulse* meetings (see Paper II). Methods and tools for analysis include product testing, mock-ups, lab tests, LCAs and economic calculations, among others. Evaluation is usually done through for example A3 reports, matrix-based evaluations, and even gut feeling at board meetings (see Paper II). Support in the form of MCDM was not found to make part of the design practitioners' repertoire of support.

RQ2 How could manufacturing companies be better supported for designing effective and resource-efficient offerings in the conceptual design stage?

The emphasis on usefulness and usability is paramount in developing support. Paper VI, VII and VIII provided support with usefulness and usability in mind. Paper VI provided a more structured way to develop support and help researchers and practitioners select an appropriate one. Paper VII showed a tool based on guidelines to assist design practitioners improve the resource efficiency of their offerings without having to do a full LCA. Paper VIII addressed systems thinking with the proposed method called CFMEA which was deemed useful for practice.

RQ3 What knowledge is needed for manufacturing companies to design effective and resource-efficient offerings in the conceptual design stage?

Papers III clarified what is meant by transdisciplinarity and showed how knowledge can be found in different disciplines. The focus on knowledge needs to be enhanced since currently academia has not thoroughly exploited insights found in different disciplines as presented in Paper IV and V. Paper IV provided insights to show what engineering design can learn from marketing. Paper V provided evidence of the lack of research in knowledge for the case of ecodesign implementation and points out that knowledge needs include: lifecycle analysis, materials and their selection, energy efficiency, legislation, and management while relevant for this knowledge are the skills of: communication, systems and lifecycle thinking. The skills of communication and lifecycle thinking were also found in Paper II and VI.

6.2 Meeting the aim of the research and answering the overarching question

In Chapter 1, the aim was stated as follows: to propose useful and usable support during the conceptual design stage of effective and resource-efficient offerings by using a pragmatic paradigm and a cross-disciplinary research approach.

The aim can be said to have been met in different ways. Papers I and II looked at support used and needs from companies, which helped in determining what type of support is currently in place and derived needs in, for example, communication and lifecycle thinking. Additionally, systems thinking was also suggested as a necessary skill in Paper V. Papers VI, VII, and VIII provided “could be” useful and usable support. Paper VI evaluated the support with use cases and Paper VII with a questionnaire answered by the user of the support, a designer, in terms of usefulness and usability. Papers III, IV, and V pointed out the main gap identified in this research: knowledge and skills of the user of the support. Paper III showed how knowledge could be produced in a cross-disciplinary manner by clarifying the different types and possible applications. Paper IV is a direct application of interdisciplinary research, bridging the gap between engineering design and marketing. Paper V is an example of TD I with a knowledge holder who can carry out ecodesign in industry.

Finally, **how can design researchers better support industry?** The answer is that this research showed that support could not only address methods and tools for carrying out design activities but also that academic researchers could **support the knowledge and skills of design practitioners (the users of the support)**. This can be better achieved by using a pragmatic and cross-disciplinary approach.

6.3 Future research

From the initial focus on methods to today’s ever-expanding field of design, a re-focus on knowledge and skills, that is, the competence needed to design effective and resource-efficient offerings, may provide a much-needed bridge between academia and industry.

The major findings point at closer collaboration and common understanding as beneficial. Before embarking into advanced theories, the field of design could investigate, in depth, design in practice. For this, research methods that require closer collaboration with industry, such as action research and ethnography, may provide a more realistic view of design or what the author of this thesis would like to coin as **realkonstruktion**: design research that has a two-way flow of data, information, knowledge, and relevant skills that develops concepts with academia and industry with evaluation points as if developing a new product.

The transferability of the results can also be enhanced in future research, for example, through surveys or comparative literature reviews, and evaluate the applications in different contexts. This is because this research was limited by the Swedish context.

Moreover, closer collaboration with industry to enable the co-creation of support using a transdisciplinary approach where researchers facilitate rather than dictate the type of support using pragmatism seems to be a paradigm shift beneficial for design research and practice. Knowledge from other disciplines, such as information systems that have more experience with the pragmatic paradigm to address useful knowledge and usability for practice, could be relevant for product designing research to learn from.

“I see and I forget. I hear and I remember. I do and I understand.” — a proverb usually attributed to Confucius 551- 479 BCE.

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