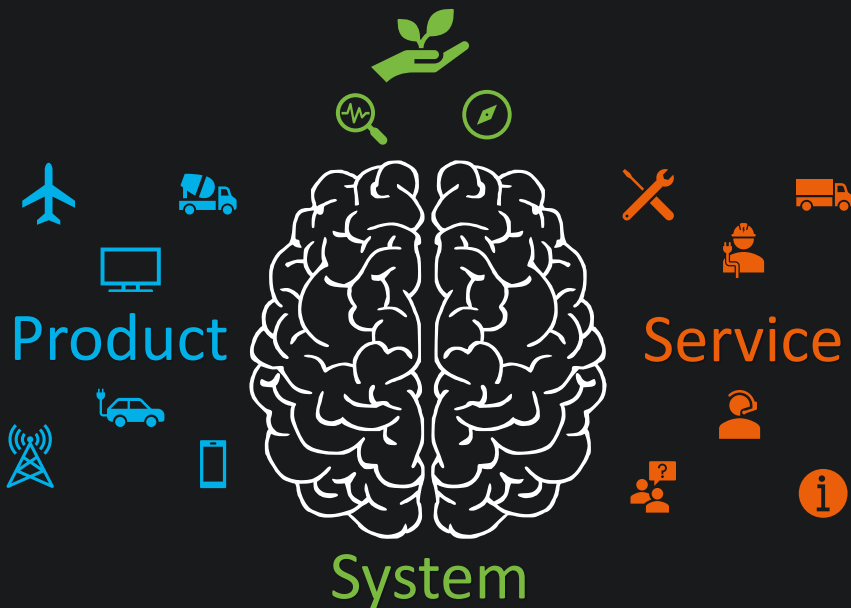


Understanding and Supporting Product-Service System Designing

Preliminary Insights and Support for Designing
Resource-Efficient and Effective Solutions

Abhijna Neramballi



Linköping Studies in Science and Technology
Licentiate Thesis No. 1877

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Cover conceptualized and designed by Shwetha VC and Abhijna Neramballi. The image of the brain represents the cognitive aspect of the research. While, the blue icons placed left of the brain represent the cognitive space of product design, the orange icons placed to the right of the brain represent the cognitive space of service design. The combination of the two cognitive spaces represents the cognitive space of product-service system design. The green icons of a magnifying glass and a compass arranged at the top of the brain represent descriptive and prescriptive dimensions of this research, respectively. The green icon of the hand with the sapling represents the practical implications of this research in terms of enhanced environmental performance of industrial activities.

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ABSTRACT

This licentiate thesis aims to establish the basis for scientifically understanding and supporting the cognitive processes involved in the conceptual design of resource-efficient and effective product-service systems (PSSs). The research carried out is transdisciplinary in nature and includes both prescriptive and descriptive studies.

First, the cognitive nature of conceptual PSS designing is investigated. Multiple pre-experimental protocol studies in a laboratory setting are carried out to do so. The cohort of these explorative studies includes experienced industrial practitioners conceptually designing a resource-efficient PSS. These descriptive studies provide quantitative insights into the cognitive effort expended by designers on various design issues and processes during conceptual PSS designing and its potential differences to conceptual product designing. These insights form the basis for future research that can eventually shine light on this complex process with statistically significant empirical results.

Second, the essence of extant prescriptive PSS design principles, methods and tools is distilled through a literature analysis and synthesis of the state of the art. Subsequently, important aspects that need to be considered during conceptual PSS designing are consolidated in the form of a PSS design schema.

Third, a design navigator named lifecycle-oriented function deployment (LFD) is developed. LFD is essentially a contextual decision-making support tool, developed to guide the conceptual designing of environmentally benign PSSs. This tool informs the designers regarding the potential environmental impacts of specific design parameters of an existing offering. It subsequently guides the designers in the redesign of this existing offering into a PSS with relatively benign environmental impacts.

Fourth, the effects of the two proposed prescriptions are tested empirically. True experimental protocol studies are carried out in a laboratory setting to test the effects of the prescriptive PSS design schema on the cognition of PSS designers. LFD is applied in an industrial case study using the action design research method, to support the conceptual redesign of an existing product-centric offering into an environmentally benign PSS. Environmental impacts of the PSS concepts generated using LFD are then evaluated in comparison to that of the existing offering, using simulated lifecycle assessment. A semi-structured interview is carried out to evaluate the utility and usability of LFD, with the company personnel involved in the conceptual redesign process.

This licentiate thesis is an effort to effectively design the future research work of the author. This future work will aim to support and establish generalizable scientific knowledge regarding the conceptual designing of resource-efficient and effective PSSs.

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As I look back on the past two and a half years of my PhD, I would like to pay tribute to everyone who has supported me in my research journey.

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List of appended papers

Paper 1: Neramballi, A., Sakao, T., & Gero, J. S. (2018, July). What Do Experienced Practitioners Discuss When Designing Product/Service Systems? In *International Conference on-Design Computing and Cognition* (pp. 361-380). Springer, Cham.

My contribution to Paper 1: As the first author of this paper, I was involved in the conceptualization, data collection and analysis, and writing of several sections of the paper. I also presented and defended this research in the above-stated conference.

Paper 2: Sakao, T., Neramballi, A. (2020). A product/service-system design schema: Application to big data analytics. (submitted to an ISI journal) (under review).

My contribution to Paper 2: As the second author of this paper, I was involved in the conceptualization, literature analysis and synthesis, and writing of sections related to PSS design. I briefly contributed to a few other sections of the paper as well.

Paper 3: Neramballi, A., Sakao, T., Willskytt, S., Tillman, A.-M., A design navigator to guide the transition towards environmentally benign Product/Service Systems based on LCA results. (submitted to an ISI journal) (under review).

My contribution to Paper 3: As the first author of this paper, I was involved in the conceptualization, method development, theoretical and empirical data collection and analysis. I was also significantly involved in the writing of several sections of the paper.

Paper 4: Neramballi, A., Sakao, T., & Gero, J. S. (2019). Effects of a design support on practitioners designing a Product/Service System-a case study. In *Human Behaviour in Design* (pp. 11-22).

My contribution to Paper 4: As the first author of this paper, I was involved in the conceptualization, empirical data collection and analysis. I was also significantly involved in the writing of several sections of the paper. I also presented and defended this research in the above-stated conference.

Related Papers

Sakao, T., Liu, Y., & Neramballi, A. (2019). Enhancing PSS design through big data, IoT and bigdata analytics. In *Spring Servitization Conference 2019* (pp. 197-205).

Matschewsky, J., Brambila-Macias, S.A., Neramballi, A., Sakao, T. A method for the development and selection of design methods – Investigating the design of resource-efficient offerings. (submitted to an ISI journal) (under review).

Neramballi, A., Sakao, T., & Gero, J. S. (2020). How do designers think in systems? – Empirical insights from protocol studies of experienced practitioners designing Product-Service Systems. In *International Conference on-Design Computing and Cognition* (accepted). Springer, Cham.

Glossary

Circular Economy: a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops (Geissdoerfer *et al.*, 2017).

Cognition: the mental action or process of acquiring knowledge and understanding through thought, experience, and the senses (Oxford Dictionary).

Design: to create, fashion, execute, or construct according to plan (Merriam-Webster).

Design Navigator: is a category of design method that considers the context of the design activity (author's own).

Design Support: what supports design activities (Mistra REES, 2019).

Efficient: maximum ratio of an output to the corresponding input (ISO/TR11065, 1992).

Effective: producing a decided, decisive, or desired effect (Merriam-Webster).

Product-Service System: a mix of tangible products and intangible services designed and combined so that they jointly are capable of fulfilling final customer needs (Tischner, Verkuijl and Tukker, 2002).

Resources: any asset (human, physical, information or intangible), facilities, equipment, materials, products or waste that has potential value and can be used.

Schema: refers to a structured framework or an outline (author's own).

Offering: offering is a suggestion of a solution, which is defined as a specific way of satisfying one or more needs with a product and/or service in a defined context (Mistra REES, 2019).

Ontology: a set of concepts and categories in a subject area or domain that shows their properties and the relations between them (Oxford Dictionary).

Abbreviations

ADR – Action design research

CE - Circular economy

DRM - Design research methodology

DS - Descriptive studies

EO - Existing offerings

FBS - Function-Behavior-Structure

LCA - Lifecycle assessment

LFD – Lifecycle-oriented function deployment

PSS - Product-service system

QFD - Quality function deployment

PS - Prescriptive studies

PBSA - Pahl and Beitz' systematic approach

RO - Redesigned offering

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*“The only way to make sense out of change is to plunge
into it, move with it, and join the dance.”*

– Alan Watts

Preface

The human activity of designing is an important catalyst for both economic and anthropogenic changes. The primary goal of designing is to change existing situations into preferred ones (Simon, 1969) and the importance of this activity has been recognized throughout history (Gero, 1990). Small decisions taken during this complex activity can potentially have huge implications. For example, London (1932) introduced the design concept of planned obsolescence of products in an effort to overcome the devastating worldwide economic crisis widely known as *The Great Depression*, prevalent in the 1930s.

Planned obsolescence is a conscious design decision taken by manufacturers to shorten the useful life of products being introduced to the market in order to stimulate repeated consumer spending on new and updated products (Bulow, 1986). This design measure, together with the consumerist theories of Keynesian economics (Keynes, 1937), were considered as potential solutions to overcome the financial crisis in the United States, as the measure was expected to drive up the demand for products and subsequently increase mass production and large-scale employment.

In recognition of its economic potential, planned obsolescence was adopted and widely practiced by several manufacturing companies (Buck, 2017). It was also referred to in academia as “a necessary condition for technological innovation” (Fishman, Gandal and Shy, 1993). Although this design practice, together with Keynesian economics, contributed significantly to the revival of the economy during the 1930s and the economic boom in the 1950s, it has been detrimental to the environment (Satyro *et al.*, 2018). This type of industrial practice is fuelled by the “take-make-dispose” resource consumption pattern, which is characteristic of the linear economic paradigm (EMF, 2013).

This unsustainable pattern of resource extraction and subsequent consumption is contributing to several intensifying environmental challenges such as climate change, water and air pollution, resource depletion and several socio-economic challenges that accompany these drastic problems. The consequences of these challenges are an example of how the resource-intensive, large-scale artificial systems designed by humans have contributed towards a situation that does not appear to be in the best interest of our species (Klotz *et al.*, 2019). Once again, the complex activity of designing might be the key to changing the course of this grim trajectory.

The growing importance of design in our society is emphasized by Nigel Cross, as he remarked, “*everything we have around us – our environments, clothes, furniture, machines, communication systems, even much of our food – has been designed. The quality of that design effort therefore profoundly affects our quality of life. The ability of designers to produce efficient, effective,*

imaginative and stimulating designs is therefore important to all of us.” (Cross, 2006, p.15). Cross further indicates that even though designing has a significant influence on everything around us, there is limited understanding regarding its nature, as he states, “...it is important, first of all, to understand what it is that designers do when they exercise this ability.” (Cross, 2006, p.15). In order to overcome the onset of the ecological and socio-economic challenges by unsustainable design and manufacturing practices of the past, there is a need to support and improve the scientific understanding of design behavior or the abilities of designers to design resource-efficient and effective solutions (REES)¹.

An international *Nature Sustainability* expert panel has recently highlighted the untapped potential of design behavior in mitigating the prevalent sustainability challenges (Klotz *et al.*, 2019). This panel has identified twenty high-priority research questions that both define and advance the focus of research on design behavior for sustainability (Report of the International Expert Panel on Behavioral Science for Design, 2019). Some of the key research issues important to understand and influence design behavior for sustainability, as highlighted in the report (*ibid*), include: *What cognitive models do (and should) designers bring? What cognitive shortcuts do (and should) designers use? What organizational process changes should be prioritized? And: How can researchers and practitioners work together?*

In my PhD research, I attempt to address a few of the above-highlighted research issues concerning design behavior for environmental sustainability. In this thesis, I develop a basis for improving the scientific understanding of how experienced practitioners from the manufacturing industry design REES, while also aiming to support and enhance their endeavor. This licentiate thesis represents the halfway point of my PhD journey and will serve as a blueprint for my doctoral dissertation.

¹ Resource-efficient and effective solutions (REES) is framed as an umbrella term for environmentally sustainable or environmentally benign or circular solutions.

Chapter 1 – Introduction

1.1 Course Correction – Destination Circular Economy

The global resource extraction rate has steadily accelerated over the past century to sustain the intensifying demands of our consumerist societies and the manufacturing companies operating in the linear economic paradigm. Although this persistent paradigm has fuelled large-scale manufacturing and contributed significantly to the global economy, it has had devastating impacts on the environment. Under this unsustainable paradigm, the rate of resource use has more than tripled, from 27 billion tons per year in 1970 to 92 billion tons per year in 2017 (UNEP, 2019).

With an increasing global population and a rising average wealth of society, the rate of resource extraction is expected to rise up to 183 billion tons per year by 2050 (UNEP, 2016). This unsustainable trend of resource extraction and subsequent processing is estimated to contribute to over 90 percent of the total global biodiversity loss, stress on water sources and over half of the total climate change impacts (UNEP, 2019). These developments increase the risk of causing irreversible damage to the environment, and consequently, pose an existential threat to humanity (Steffen *et al.*, 2015).

As a consequence of the festering environmental challenges, manufacturing companies are also facing several issues such as increasing resource costs, resource supply risk and increasing market competitiveness (Jackson, 2009; UNEP, 2019). Despite these potential risks, many manufacturing companies continue to adhere to this unsustainable economic paradigm (RSA, 2013). There is an urgent need for the manufacturing industry to transition away from the linear economic paradigm towards a more resource-efficient and circular one.

Consequently, interest in the transition towards a circular economy (CE) is increasingly gaining traction among several important actors, including the manufacturing industry (EMF, 2013; UNEP, 2019), academia (Geissdoerfer *et al.*, 2017) and governing bodies (European Commission, 2017). A circular economy (CE) is defined as “a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops” (Geissdoerfer *et al.*, 2017).

The manufacturing industry is expected to play a key role in facilitating the demanded transition towards a CE (Lindahl, 2018), especially since the industrial offerings within such a paradigm are expected to be restorative by design, in which the constituent products, components and materials need to be maintained at their highest value and utility at all times (Webster, 2015). However,

this transition should not be at the cost of the economic performance of the manufacturing industry. Along with the demanded industrial transition towards a CE, there is a growing need to decouple economic growth from resource use and environmental costs (UNEP, 2019).

Apart from the demands for the transition towards a CE, manufacturing companies are further challenged by intensifying market competitiveness, reducing margins for material-intensive products, and changing customer preferences (EU Business Innovation Observatory, 2016). Servitisation (Vandermerwe and Rada, 1988), which is often referred to as the process of increasing revenue for manufacturers from services, is widely considered in the literature as a potential solution to the aforementioned business challenges (Oliva and Kallenberg, 2003; Neely, 2008; Baines *et al.*, 2017).

In recognition of this potential, many manufacturing companies are integrating services into their core product offerings (EU Business Innovation Observatory, 2016). These types of service integrated offerings, commonly referred to as Product-Service Systems (PSSs), are also expected to have relatively benign environmental impacts and a high potential for resource efficiency (Goedkoop *et al.*, 1999; Mont, 2002) in comparison to conventional stand-alone products.

1.2 Product-Service Systems – a potential Route to the Circular Economy?

A PSS can be defined as “a mix of tangible products and intangible services designed and combined so that they jointly are capable of fulfilling final customer needs” (Tukker and Tischner, 2006). In the traditional product-centric business setting, most of the added value is derived from the production processes that transform raw materials into products to be used by customers (Mont, 2002). However, in a PSS-oriented business setting, added value for customers can potentially be derived from multiple sources, depending on the type of business model.

For example, in the use or result-oriented PSS, the focus is on fulfilling customer needs and increasing value with an appropriate combination of products, services and business models (Tukker, 2004). In these cases, the customers do not necessarily have to pay for the ownership of the product as such, but for the fulfilment of their needs (*ibid*) by receiving services or functions of products owned by the provider. Consequently, it will be in the interest of the provider to reduce the amount of resources consumed per the unit of offering, since the profit is dependent on the cost per unit of service provided or resources consumed during the use phase (Vezzoli *et al.*, 2015).

The providers are also incentivized by the prospect of introducing these types of offerings, as the integrated services have the potential to generate predictable revenue streams and provide a competitive edge in highly saturated, product-

intensive markets (EU Business Innovation Observatory, 2016). Irrespective of the type of the business model, the services and products integrated within the PSS solution can be designed with a lifecycle perspective to ensure that the constituent product parts have an extended useful life, consume minimum resources during the use phase and have circular end-of-use strategies (Lindahl, 2018). Potential benefits of PSSs have been discussed extensively in the literature, among which two of the most highly discussed benefits are the potential for market differentiation and reduced environmental impacts (Annarelli, Battistella and Nonino, 2016).

Empirical evidence regarding the economic and environmental benefits resulting from a transition towards the design and provision of PSSs are also reported in the literature (e.g., Lindahl, Sundin and Sakao, 2014; Matschewsky, 2016). Due to these reasons, PSSs are widely regarded as one of the most effective routes available for the societal transition towards a resource-efficient society and CE (Tukker, 2015). Thus, the PSS is chosen as the core object of study in this thesis. Despite its documented potential, a mere transition to PSSs may not necessarily guarantee a CE, nor necessarily lead to an absolute decoupling of economic growth from resource use or environmental costs (Tukker, 2015; Kjaer *et al.*, 2019).

1.3 Research Clarification

1.3.1 Introducing the Research Motivation

A potential PSS needs to be designed, developed and delivered in specific ways to realize the wide spectrum of the envisioned benefits (Cook, Bhamra and Lemon, 2006; Vezzoli, Kohtala and Srinivasan, 2014; Vasantha, Roy and Corney, 2015). In the literature, the role of design is especially considered to be critical for the effective development of a PSS and is expected to vary significantly in comparison to the conventional approaches of designing products (e.g., Morelli, 2002; Akasaka *et al.*, 2012; Matschewsky, Kambanou and Sakao, 2018). Due to the predicted disparities in the nature of designing conventional products and PSSs, manufacturing companies are seeking dedicated support to effectively design PSSs (Morelli, 2002; Vasantha *et al.*, 2012).

The conceptual design phase is widely recognized in the literature to be relatively more important than the other phases due to its influential role in determining the fundamental characteristics of the contents being designed (French, 1999). During this phase of design, designers aim to identify basic principles and outline the premises of concepts (Kannengiesser and Gero, 2017). The conceptual design phase is considered to be critical for PSS development (Geum and Park, 2011) and yet is relatively less understood in comparison to the other phases. Thus, it is chosen as the core process of study of this thesis.

The rising need for improved understanding of and effective support for conceptual PSS designing points towards an increasing demand for scientific PSS design research. The approaches suggested by the domain of design science research could potentially be utilized to address this rising demand. Two of the primary objectives of design science research are 1) to increase the understanding of designing by formulating and validating models and theories of the phenomenon, and 2) the development of knowledge, methods and tools based on the developed theories to improve the design process (Blessing and Chakrabarti, 2009).

1.3.2 Uncovering the Gaps in PSS Design Research

A deep understanding of designing can only be developed when all its dimensions, such as process (structure and dynamics of the complex activity being studied) and content (design problems and emerging solutions), are connected to the context in which the activity is taking place and also to the designers who carry out the activity (Dorst, 2008). This multi-dimensional activity of designing can be observed and described in different scales of granularity, ranging from the cognition of the designers in the micro-scale to the overall progression of design processes in the macro-scale (Cash, Hicks and Culley, 2015).

Significant research effort has been expended on describing and prescribing the macro-scaled processes of PSS designing in the literature (Meier, Roy and Seliger, 2010; Matschewsky, Kambanou and Sakao, 2018). This extensive research effort points towards multiple disparities between PSS designing and conventional product designing. Although the two domains vary significantly in terms of the macro-scaled dimensions of designing, it is unclear how these differences influence the designers' cognition.

This lack of understanding can be attributed to the limited availability of scientific insights into the cognitive nature of conceptual PSS designing. These insights into the micro-scale dimensions of conceptual designing are important since the computational and other support methods or tools that are developed to enhance the design activity need to be aligned with the designers' cognition (Cross, 2006; Chandrasegaran *et al.*, 2013).

To develop effective PSSs, product and service designers need to collaboratively design the contents in an integrated and systemic manner (Meier, Roy and Seliger, 2010). However, in industry, products and services are often designed separately and sequentially (Matschewsky, Kambanou and Sakao, 2018). Consequently, the cognitive design spaces of product and service designers tend to be separated both spatially and temporally in industrial settings, which is not ideal for observing and understanding conceptual PSS designing.

Laboratory studies of collaborative conceptual PSS designing by product and service designers can potentially provide the required scientific insights into PSS design cognition. These laboratory studies should be designed to facilitate

unrestricted collaboration between the product and service designers during the design activity. However, there are only a few such laboratory studies that provide quantitative and reproducible insights into the micro-scaled, cognitive dimension of conceptual PSS designing (e.g. Sakao, Paulsson and Mizuyama, 2011; Shimomura, Nemoto and Kimita, 2015). Despite the valuable contributions of these studies, the frames of analyses used, and the results derived are mainly specific to the PSS design process. Consequently, the results of these studies may not be commensurable with other domains of designing, such as product designing.

Commensurable elements in the frames of analyses are crucial to enable meta-analytics across the different domains of designing (Cash, 2018), which is fundamental to build a scientific understanding of the phenomenon (Gero, 2010). These commensurable quantitative insights into the cognitive nature of conceptual PSS designing are necessary to build, test and validate theories of PSS designing. Furthermore, these insights are crucial to test if the prevalent claims of disparities between PSS designing and product designing have any scientific grounding on the cognitive level.

Although there is a substantial number of prescriptive support methods and tools, these prescriptions usually address different aspects of PSS designing. Surprisingly, there is no consolidation of this knowledge. There is a need to synthesize the essence of the extensive prescriptive PSS design research in the form of a comprehensive schema² that can provide a structured outline of the relevant issues to be considered by designers during conceptual PSS designing. This consolidated schema can also potentially contribute towards the creation of a unified PSS design knowledge schema for computational systems that can potentially support the cognitive processes of designers during conceptual PSS designing. The development of such a common knowledge schema and comprehensive knowledge support system was highlighted by Vasantha, Roy and Corney (2015) as an important trajectory for future PSS design research.

Apart from the designers' cognition, other crucial dimensions of the design activity include the content of design, such as design problems and emerging solutions, and the context of the design activity. One of the primary problems addressed during PSS designing is the reduction of environmental impacts of design solutions while considering the context of the design. Manufacturing companies seeking to transition towards the design and development of PSSs might need to redesign their existing product-centric solutions, especially since, in industry, the redesign of existing solutions is more frequent than the introduction of brand new ones (Blonigen, Knittel and Soderbery, 2017).

In the literature, several prescriptive methods and tools for supporting PSS designing with a focus on reducing its environmental impacts have been proposed (see reviews by Vasantha *et al.*, 2012; Vasantha, Roy and Corney, 2015;

² Schema, in this context, refers to a structured framework or an outline.

Brambila-Macias, Sakao and Kowalkowski, 2018). However, there is virtually no support in the state of the art that allows designers to reflect on the quantitative environmental impacts of an existing solution and thus to make informed decisions during its conceptual redesign to an environmentally benign PSS. From a practitioner's point of view, this empirical, quantitative information-based, contextual feedback regarding environmental impacts to the conceptual design phase is essential to ensure the efficacy of design or redesign of PSSs.

Dorst (2008) suggested that design research is still in a pre-scientific stage as most of the developed prescriptive design support methods and tools are not rigorously tested, thus impeding the development of knowledge in the field. This is especially relevant in the case of PSS design research, as there are limited scientific insights into the effects of prescriptive design support on the designers' cognition and on the outcomes of design, thus suggesting the need for the increased testing of such existing knowledge. Scientific insights in this context refers to the insights derived from comparisons between the observations of conceptual PSS design activities carried out with and without the interventions of prescriptions.

1.3.3 Aim and Research Questions

This thesis, to address the described research gaps, aims *to create a basis for improving the understanding of and supporting the cognitive processes of conceptual PSS designing*. Cognitive processes in this context refers to the way designers think during designing. Support in this context refers to design method, procedure, tool, means or aids that can improve the design process (Blessing and Chakrabarti, 2009). This research aim is operationalized with the following research questions (RQs):

RQ1 What is the cognitive nature of conceptual PSS designing performed by experienced practitioners?

This RQ is formulated to address the crucial gap in our knowledge (elaborated on in *Section 1.3.1*) concerning the lack of quantitative and commensurable descriptive insights into conceptual PSS designing. An answer to this question can form the basis to scientifically understand how experienced practitioners from industry distribute their cognitive design effort on fundamental design issues and processes during the design of a PSS. Cognitive design effort refers to the cognitive activities associated with designing (Kan and Gero, 2017).

The answer to this RQ is also expected to provide some early insights into comparisons between the cognitive nature of the conceptual product and PSS designing, respectively. The insights derived from the answer of this RQ will be used as a foundation for the future research of the author, which aims to characterize conceptual PSS designing based on statistically significant empirical data.

RQ2 What is the essence of existing prescriptive PSS design knowledge?

As revealed in *Section 1.3.1*, even though there is a substantial body of prescriptive design support methods and tools, consolidation of this quantized knowledge is missing in the literature. The existing design methods and tools address different dimensions of PSS designing but do not provide comprehensive guidance to designers on a generic level to conceptually design a PSS, regardless of the context.

The answer to this research question is expected to represent the essence of the existing prescriptive knowledge concerning conceptual PSS designing in the form of a prescriptive PSS design schema.

RQ3 How can the decision-making of designers be contextually supported during conceptual PSS designing to reduce environmental impacts?

Effectiveness can only be guaranteed when the means have the desired consequences at the end. As revealed in *Section 1.3.1*, there is a lack of contextual guidance for designers to make effective decisions during conceptual PSS designing based on the empirical, quantitative information regarding the environmental impacts of the existing offering being redesigned.

The answer to this RQ will present a design navigator³ that provides contextual support to designers by informing them regarding the quantitative environmental impacts of an existing offering. This navigator is expected to effectively guide the decision-making of the designers during the conceptual redesign of the existing offering to an environmentally benign PSS.

RQ4 What are the effects of the interventions of prescriptive support during conceptual PSS designing?

It was revealed in *Section 1.3.1* that there is a lack of understanding regarding the effects of prescriptive proposals for conceptual PSS designing. The answer to RQ4 will initially form the basis to study the effects of the prescriptive schema for PSS design on the cognition of the designers conceptually designing a PSS. The prescriptive schema will be the outcome of RQ2.

RQ4 will also investigate the effects of the design navigator on the potential environmental impacts of the concepts of the PSS solution being designed using the prescriptive design navigator, which will be derived as an outcome of RQ3. These answers will provide much-needed reflection to the body of research concerning prescriptive PSS designing.

³ Design navigator is a category of design method that considers the context of the design activity.

1.4 Research Scope

The following Figure 1 visualizes the scope of this research. This research is carried out in and across empirical and theoretical realms. The empirical realm represents the realm in which the activity of conceptual PSS designing is carried out, either in an industrial or laboratory setting.

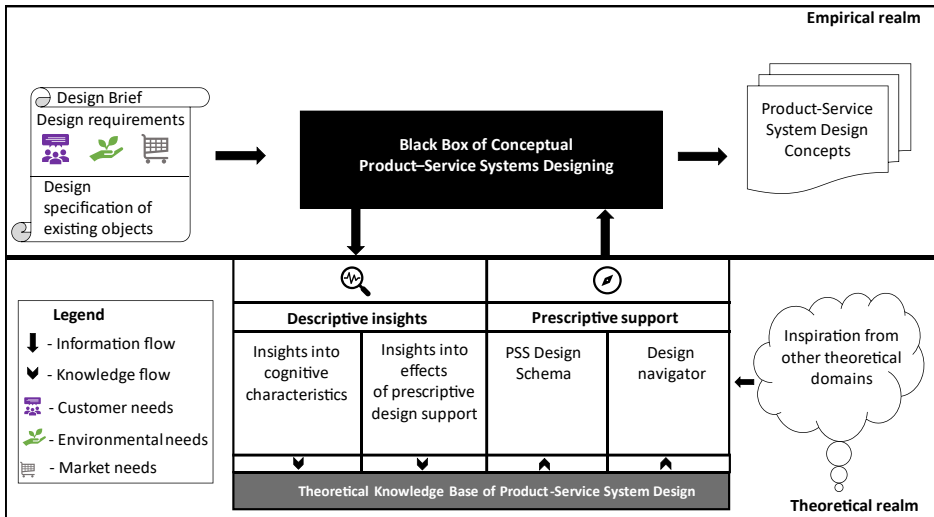


Figure 1. Visual depiction of the research scope (Author’s own).

In Figure 1, conceptual PSS designing is represented as a black box in the empirical realm. The input to this black box is represented by the information within the design brief, which includes information regarding the requirements of the design in terms of customer, market and environmental needs. If the PSS is conceptually designed based on an existing design solution, then the design brief can include information concerning the design specification of the existing solution. This design brief is used by designers to conceptually design the PSS. The potential output of this black box is represented by the PSS based REES design concepts that are generated by the practitioners as a result of the conceptual design process.

This thesis will provide both descriptive insights into, and prescriptive support for, conceptual PSS designing. The research (illustrated in the theoretical realm in Figure 1) will contribute to the theoretical knowledge base of PSS design with empirical insights into the cognitive effort expended by experienced practitioners on design issues and design processes during conceptual PSS designing. The essence of existing prescriptive PSS design knowledge is consolidated as a prescriptive schema to support the conceptual design process. In addition, a design navigator is developed and prescribed based on the extant

knowledge from the theoretical bases of PSS design and other theoretical domains. Insights into the effects of these two prescriptions will then be provided to enrich the theoretical knowledge base of PSS design.

1.5 Research Project

This licentiate thesis work is part of a larger program, titled MISTRA Resource-Efficient and Effective Solutions (REES). It is a research program based on circular economy thinking, run by a consortium of leading Swedish universities, small, medium and large manufacturing industries and relevant societal actors. This research was part of the design project within the overall program. Phase 1 (four years) of this research program concluded in November 2019, which also marked the beginning of Phase 2 (another four years) of the same program. Phase 2 will run until the end of 2023.

1.6 Thesis Outline

The rest of the thesis is laid out as follows. Chapter 2 presents the theoretical framework, which describes the various concepts, models and theories that are used in this research. Chapter 3 then describes the research design. Next, Chapter 4 presents the results of the research in connection to the research questions, derived from the appended papers. Discussions regarding the scientific quality, meta-analysis, contributions and practical implications of the results are also presented in this chapter. Finally, Chapter 5 presents the conclusions which answer the research questions and future research directions.

“The task is, not so much to see what no one has yet seen, but to think what nobody has yet thought, about that which everybody sees.”

— Erwin Schrödinger

Chapter 2 – Theoretical Framework

2.1 Design Research – An Investigation of the State of the Art

2.1.1 Historical Overview

Due to its impact on society and inherent complexity, designing is considered to be a significant intellectual activity (Gero and Mc Neill, 1998). Outcomes of this complex activity can include artifacts such as products, ideas or certain technologies (Blessing and Chakrabarti, 2009). During designing, requirements formulated as functions that embody the purpose of the artifact being designed are transformed into design descriptions (Gero, 1990).

Dorst (2008) suggested that in order to develop the field of design research as a scientific discipline, the complex activity of designing needs to be initially observed, then described before creating models of the phenomenon that explain the observations and descriptions. These explanatory models could then be used to prescribe the ways in which the practice of designing can be improved with methods and tools that support the practitioners (Dorst, 2008).

According to Cross (2006, p. 95), some of the earliest attempts to scientise design can be traced back to the 1920s, during which a few academics highlighted the need for rational approaches to the construction of the artificial. Bayazit (2004) suggested that these aspirations to scientise design were driven by global events such as World War 2 and the Cold War. These global events vastly diminished labor forces but simultaneously increased the demand for manufactured goods across Europe and the US, thus creating a need for scientific approaches to design and production.

Cross suggested that the aspirations to scientise design culminated in a conference on design methods held in London in 1962 by Jones and Thornley (1963), which significantly contributed to the launch of design methodology as a field of scientific enquiry (Cross, 2006, p.95). The 1960s were heralded as the “design science decade” by the well-known technologist Buckminster Fuller, as several notable contributions to research in design emerged in this productive span of 10 years. Examples of these notable contributions include the book chapter by Sidney Gregor titled “Design Science” (Gregory, 1966) and the seminal work titled *Sciences of the Artificial* by the late Nobel Laureate Herbert A. Simon (Simon, 1969, 1996).

2.1.2 Science of Design

One of the goals of design research is to improve the understanding of design (Gero, 1990). This goal is operationalized by the science of design, which refers to “a body of work which attempts to improve our understanding of design through scientific (i.e., systematic and reliable) methods of investigation” (Cross, 2006, p. 99). There is a need to formulate and validate models and theories of the phenomenon to increase our scientific understanding of designing (Blessing and Chakrabarti, 2009). To formulate and test models of designing, empirical data of designers designing is necessary, and one way of accessing this data is through the study of design cognition (Gero, 2010).

There is an increasing interest in improving the scientific understanding of cognitive nature of designing across different domains, since it is expected to drive the development of the next generation of computational support tools (Goel *et al.*, 2012; Chandrasegaran *et al.*, 2013) and support methods for designing. There is a widening gap between the increasing amount of design support being developed by academics and the level of its uptake by practitioners in industry (Schönheyder and Nordby, 2018). This gap further highlights the need for an improved scientific understanding of the cognitive nature of conceptual PSS designing and for the design support being developed to be grounded on this understanding.

There is a need for commonly used and agreed upon analytical tools to scientifically study design cognition (Gero, 2010). Gero (2010) further elaborated that the fundamental issues and processes involved in designing are not specifically related to any design task, designer or situation. This opens the possibility to generate generic analytical tools that can be used across different domains and environments of design (*ibid*) to analyze designing. Below, two such generic analytical tools are presented, which have been previously used to increase the understanding of different domains of designing.

2.1.3 Function-Behavior-Structure Ontology

Prior to the 1990s, design research was limited to computer-based models, and empirical research regarding characteristics of design was nonexistent (Gero and Mc Neill, 1998). Since the 1990s, there has been a growing consensus in the literature regarding the claim that, like all science, there is a regularity in designing that transcends any individual or design task or type of artifact being designed (Gero, 2010). Gero (2010) suggested that this regularity in designing can be captured empirically in terms of fundamental design issues and processes by one or more scientific schemata. The function-behavior-structure (FBS) schema is one such formal representation of fundamental design issues and design processes (Gero, 1990).

The schema includes three main classes of variables that describe the different issues of the design object and are described as follows (Gero, 1990; Gero

and Kannengiesser, 2004): 1) function (F), which describes the teleology of an aspect of the design object, i.e., what it is for; 2) behavior (B), which describes the attributes that are derived (Bs) or are expected to be derived (Be) from the structure (S) of the design object, i.e., what it does (Bs) or what it is expected to do (Be); and 3) structure (S), which describes the components of the design object, i.e., what it is. Design description (D) represents documentation. Sometimes, recipients of the artifact being designed also specify explicit requirements (R), which are translated to function by the designers during designing. The schema also represents designing as a series of eight processes linking the design issues F, Be, Bs, S and D at the different stages of design (Gero, 1990; Gero and Kannengiesser, 2004; Kannengiesser and Gero, 2015) and is depicted in Figure 2.

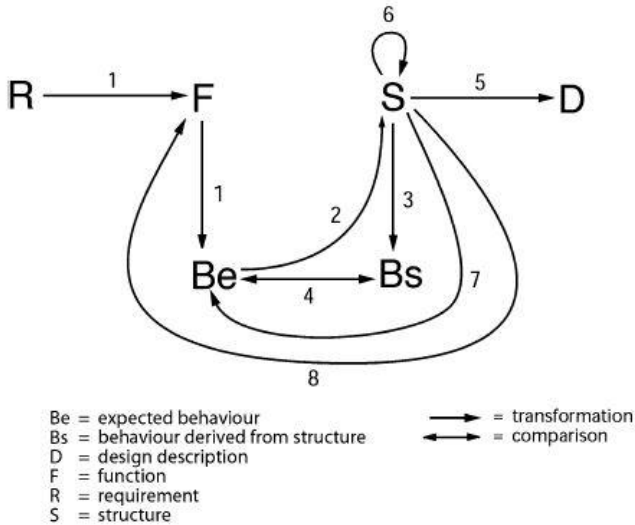


Figure 2. Design issues and processes in the FBS framework, adopted from (Kannengiesser and Gero, 2015).

The eight processes are claimed to be fundamental in designing and are described as follows (ibid): 1) Formulation, which transforms the design requirements (R) in terms of function (F) into behavior that is expected (Be) to facilitate this function; 2) Synthesis, which transforms the expected behavior (Be) into a solution structure (S) that displays the expected behavior (Be); 3) Analysis, which generates the behavior (Bs) of the solution structure (S); 4) Evaluation, which is the assessment of a generated solution by comparing the behavior of the structure (Bs) and the expected behavior (Be); 5) Documentation, which is the documentation of the design description (D) for further stages of development; 6) Reformulation 1, which is if the assessed behavior of generated

structure solutions (Bs) is unsatisfactory, generated structure variables are subjected to changes in the design state space; 7) Reformulation 2, which is if the assessed behavior (Bs) of the generated structure solutions are unsatisfactory, expected behavior (Be) variables are subjected to changes in the design state space; and 8) Reformulation 3, which is if the assessed behavior of generated structure solutions (Bs) is unsatisfactory, derived function variables are subjected to changes in the design state space.

This framework has been utilized in several studies, which have provided significant empirical insights into how designers design products (Gero and Mc Neill, 1998; Mc Neill, Gero and Warren, 1998; Kannengiesser and Gero, 2015). Since the framework is independent of the design object, task, designers' experience or the design environment, it can be applied across different scenarios and disciplines while obtaining commensurable results (Kan and Gero, 2017). This commensurability is crucial, as it is imperative to build on the work of other researchers to scientifically develop a research domain (Gero, 2010). The application of the FBS ontology in a wide variety of domains of designing is well documented (see the review by Hay *et al.*, 2017). Even though this is not the only framework that can capture design issues and processes, it is indeed the most used one, with one order more instances of use than other frameworks (Gero, 2010).

2.1.4 A Framework for Systems Hierarchy

Cross (2006) suggested that a design process entails the solving of ill-defined problems. Designers often employ different strategies to solve these complex problems. One such commonly used strategy is the decomposition and recomposition of design problems (Song *et al.*, 2016). Using this strategy, designers often analyse design problems in different levels of abstraction that can range between the high systems level and detailed elemental level (Mc Neill, Gero and Warren, 1998).

During problem decomposition, design problems are broken down from a higher systems level to a lower elemental level of abstraction in terms of smaller sub-problems, and during problem recomposition, the sub-problems in the lower elemental level are recombined to form systemic problems on a higher level (Chandrasekaran, 1990). Based on the work of Mc Neill, Gero and Warren (1998), Song *et al.* (2016) proposed an analytical framework to capture how designers employ this strategy of problem decomposition and recomposition during designing, which is described in Table 1.

Table 1. A framework to capture levels of problem abstraction by designers during designing (adapted from Song *et al.*, 2016).

Level of problem abstraction	Definition	Representation of levels in the thesis
1. Systems	Designers focus on the problem as an integral whole.	S (Systems)
2. System and Sub-systems	Designers focus on interactions between sub-systems.	I (Interactions)
3. Subsystems	Designers focus on the details of the sub-systems.	D (Discrete)

Results from the study by Song *et al.* (2016) indicate that there are differences in the way engineering experts and novices employ the strategy of problem decomposition and recomposition during designing. This indicates that this type of analytical framework can potentially be used to capture characteristic differences in the way two different cohorts of designers carry out design processes.

2.1.5 Scientific Support for Designing

Another important objective of research in design is to develop design support methods and tools that aid the designers during designing (Gero, 1990). Such support facilitates the designers to carry out designing systematically and rationally (Bayazit, 2004) and aids in the improvement of the design process (Blessing and Chakrabarti, 2009). There is a plethora of such prescriptive support in the design literature, ranging from design methodologies or schemata based on models of design processes to more specific design methods or tools that support certain aspects of these processes.

Design methodologies or instructional schemata are crucial to support designers due to the high inherent complexity of design processes, associated risks and costs and the need for improved efficiency of the design process (Cross, 1989). These methodologies usually offer more of a generic, algorithmic and systematic procedure for designing. Several such prescriptions to support and improve the process of engineering design were proposed in the 1980s (Bayazit, 2004; Cross, 2006) such as *Principles of Engineering Design* (Hubka, 1982), *Engineering Design* (Pahl and Beitz, 1984, 2007), *Conceptual Design for Engineers* (French, 1985, 1999), *A Scientific Approach to Engineering Design* (Hubka and Eder, 1987) and *Product Design and Development* (Ulrich and Eppinger, 1988, 2012). These methodologies offer generic guidance for designing.

A more specialized type of support for designing is usually referred to as design methods, which can include any tools or techniques that aid the process of designing by supporting “the assessment of design problems and the development of design solutions” (Cross, 2007). Booker (2012) listed a few popular design methods that have been widely adopted in industry such as quality

function deployment (QFD), failure mode and effects analysis (FMEA), fault tree analysis, design for assembly (DFA), design for manufacturing (DFM), poka-yoke and Taguchi's robust (tolerance) design (RB). The systematic approach to designing by Pahl and Beitz (2007) and QFD by Akao (1990) are utilized in this thesis and are described below.

Pahl and Beitz' Systematic Approach (PBSA) to Designing

As uncovered above, there are many proposals of systematic and methodological design procedures that are expected to lead designers towards good solutions (Cross, 2006). One such systematic approach to designing was proposed by Pahl and Beitz (2007) (PBSA). It is described as a sequence of four stages: 1) task clarification, 2) conceptual design, 3) embodiment design and 4) detail design. Since the focus of this thesis is on the conceptual design stage, only the second stage of PBSA is considered here. The conceptual design stage has the following sequence of steps (Pahl and Beitz, 2007):

1. Abstract to identify the essential problems
2. Establish function structures: overall function – subfunctions
3. Search for working principles that fulfil the sub-functions
4. Combine working principles into working structures
5. Select suitable combinations
6. Firm up into principle solution variants
7. Evaluate variants against technical and economic criteria

Pahl and Beitz' Systematic Approach (PBSA), originally published in 1977, is one of the most widely referenced systematic procedures for designing in academia (Kannengiesser and Gero, 2017). It is based on the experience of the authors themselves, who are established researchers in design, and is also based on the observations of designers in practice (ibid). Wallace and Blessing (2000) suggested that PBSA has significantly influenced several other well-known models of designing, such as *The Mechanical Design Process* by Ullman (1992), and it is a part of the curriculum for engineering design education in several countries (Kannengiesser and Gero, 2017).

Quality Function Deployment

The effectiveness of a design object is usually determined by its ability to meet the requirements of the design. Generally, design requirements are incorporated into the design process right from the early stages (Pahl and Beitz, 2007). Quality function deployment (QFD) is one of the most powerful design methods that can be used to efficiently and effectively support designers to translate the design requirements in terms of the characteristics and components of the design object (Fargnoli and Sakao, 2017). It was originally developed and proposed by Akao (1990) to support product development processes and to support the

continuous improvement of products. Since its conception, several adaptations of QFD have been proposed in academia (Fargnoli and Sakao, 2017), and it is also one of the most widely used methods in industry (Booker, 2012).

2.2 Design for Benign Environmental Impacts

Victor Papanek, in his seminal work *Design for the Real World: Human Ecology and Social Change*, suggested that “design must reflect the times and conditions that have given rise to it, and must fit in with the general human socio-economic order in which it is to operate in” (Papanek, 1985). As described in Chapter 1, the current human socio-economic order within which the manufacturing industry operates is increasingly recognized to be unsustainable. There is an urgent need for the transition towards a more resource-efficient and circular socio-economic order. Design plays a crucial role in this transition and needs to be adequately adapted to fit in with the aspired circular economic order.

Buckminster Fuller is credited by Ceschin and Gaziulusoy (2016) as one of the first to have raised concerns regarding resource limits and environmental impacts resulting from the unsustainable practices of the manufacturing industry and to have highlighted the role of design in mitigating these impacts in his influential work *Operating Manual for Spaceship Earth* (Fuller, 1969). Since then, several design initiatives have been proposed in the literature to mitigate the environmental impacts of the manufacturing industry. One of the first such initiatives is referred to as *green design practice*, which primarily focuses on the redesign of specific qualities of products in order to reduce their environmental impact (Ceschin and Gaziulusoy, 2016).

Another widely used design initiative to reduce the environmental impacts of manufacturing is referred to as *ecodesign*, which integrates environmental considerations and also a lifecycle perspective into product development (ISO, 2011). Lifecycle refers to the consecutive and interlinked stages of a product or service system, starting from raw material acquisition to final disposal. Lifecycle stages include acquisition of raw materials, design, production, transportation/delivery, use, end-of-life treatment and final disposal of the products (ISO:14001, 2015).

Ecodesign is different from green design, as the former involves the application of a lifecycle perspective while analyzing the environmental impacts of a product system in order to identify the phases with the highest impacts and subsequently to direct effective design interventions (Ceschin and Gaziulusoy, 2016). Life cycle assessment (LCA) is a powerful tool that can provide quantitative reflection regarding the environmental impacts throughout the lifecycle of product systems (Baumann and Tillman, 2004; ISO, 2006), and it has been extensively used in the past to support the ecodesigning of products (Chang, Lee and Chen, 2014). Several ecodesign tools, methods and their application in product development are investigated in detail in a number of reviews of the state of

the art (see, e.g., Pigosso, McAlloone and Rozenfeld, 2015; Rossi, Germani and Zamagni, 2016).

A more recent initiative is that of circular design (Moreno *et al.*, 2016; EEA, 2017), which is a crucial element of the promising concept of CE (EMF, 2013; European Commission, 2017). Circular design mainly focuses on increasing the useful life of products by enabling interventions such as increased durability, reuse, repair, redistribution, remanufacturing and refurbishing by applying a lifecycle and a systems perspective (EEA, 2017). In-depth details and principles concerning circular designing can be found in the literature (Bocken *et al.*, 2016; Moreno *et al.*, 2016; Lindahl, 2018). Other design initiatives to reduce the environmental and socio-economic impacts of manufacturing are explored in detail in a review by Ceschin and Gaziulusoy (2016).

In order to realize the full potential of the above-mentioned initiatives for reducing environmental impacts and resource consumption, it is essential for the design perspective to move beyond physical product systems. Environmental impacts of a product are usually spread out throughout its lifecycle and design interventions, for the product system alone may not be enough. Furthermore, economic incentives are crucial for manufacturers to adopt the various design initiatives to reduce the resource consumption and environmental impacts of the products.

One way of addressing these challenges is to incorporate and integrate intangible services into the design object, which can potentially mitigate the environmental impacts of the product throughout its lifecycle and also provide opportunities to increase revenue and market competitiveness. These integrated design objects are commonly referred to as PSSs. The PSS is the object of study of this thesis, and thus, state of the art in PSS research is explored below.

2.3 Product-Service Systems

2.3.1 Background

As described in Chapter 1, a PSS is a system consisting of combinations of tangible products and intangible services that are designed and integrated to address specific customer needs, with minimal environmental impacts. One of the earliest works on PSSs was a Dutch governmental project report on environment and economics by Goedkoop *et al.* (1999). In this report, they explored the potential of PSSs in relation to sustainability, economy and the environment.

Since its conceptualization, the PSS has received significant research interest from multiple disciplines, including business management, information systems and engineering designing (Boehm and Thomas, 2013; Tukker, 2015). In a seminal publication, Mont (2002) clarified the concept of the PSS and discussed its potential benefits and uncertainties in terms of its potential applicability and

feasibility. Since then, several definitions and concepts of PSSs have been proposed in the literature (see the review by Boehm and Thomas, 2013).

An important goal of the PSS concept is to reduce the environmental impacts of consumption (Roy, 2000; Mont, 2002). This goal was operationalized into the following objectives by Mont (2002): 1) closing material cycles, 2) reducing consumption through alternative scenarios of product use, 3) increasing overall resource efficiency and dematerialization of PSSs, and 4) providing systems solutions and efficient integration of system elements. These objectives are in line with the overarching objective of the thesis.

Several benefits, barriers and drivers of PSSs have been extensively discussed in the literature (see the review by Annarelli, Battistella and Nonino, 2016). In-depth insights into the multidimensional facets of PSS research can be found in many reviews (see Baines *et al.*, 2007; Meier, Roy and Seliger, 2010; Boehm and Thomas, 2013; Brambila-Macias, Sakao and Kowalkowski, 2018).

2.3.2 Types of Product-Service Systems

There are several types of PSSs based on the value derived from and the level of integration of the system contents. Tukker (2004) presented a widely used categorization, which is spread across a continuum of product/service content ratio. The ratio is maximum at the left end of the continuum and minimum at the right end. Based on this continuum, PSSs are categorized as follows: 1) product-oriented PSSs, which has a focus on the sale of products, complemented by certain services; 2) use-oriented PSSs, where products are central but ownership is not transferred to the users, and rather the products are shared by several users based on the business contract; and 3) result-oriented PSSs, in which the client pays the provider for the provision of a result without the involvement of a pre-determined product in the transaction. This categorization is depicted in Figure 3.

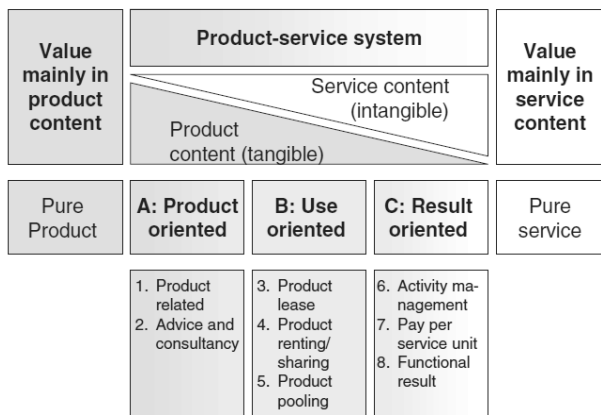


Figure 3. Classification of PSSs (adopted from Tukker, 2004).

2.3.3 Realization of Product-Service Systems

Cavalieri and Pezzotta (2012) have reviewed the state of the art and identified three recurring fundamental facets of the PSS concept in the literature. These facets include entities, lifecycle perspective and actors. The *entities* form the main contents of the PSS, which can include tangible products, intangible service elements and the channel, which is used to transfer, amplify and control the contents (Sakao and Shimomura, 2007). The channel was further broken down by Cavalieri and Pezzotta (2012) into a network of companies and infrastructure, based on the work of Mont (2002).

Subsequently, Cavalieri and Pezzotta (2012) highlighted the importance of the *lifecycle perspective*, which is the second fundamental aspect of the PSS concept. A lifecycle perspective is imperative to successfully realise a PSS, and requires the providers to extend their involvement and responsibility throughout the various stages of the lifecycle of the system contents (Aurich, Fuchs and Wagenknecht, 2006; Sundin, Lindahl and Ijomah, 2009). The acquisition of raw materials, design and production constitute the beginning of life (BOL) stage, while transportation, use-phase related services such as maintenance and repair constitute the middle of life phase (MOL) and treatment, recycling or remanufacturing or final disposal constitute the end of life (EOL) phase (Cavalieri and Pezzotta, 2012).

The final, fundamental aspect of the PSS concept is *actors*, which can include recipients of the PSS such as customers or end-users, actors within the channel, society and the environment (Mont, 2002; Morelli, 2006; Cavalieri and Pezzotta, 2012). The realization of a PSS is typically a two-stage process: design and delivery. These complexities of the PSS realization process are illustrated in Figure 4.

The various fundamental facets of a PSS need to be engineered with a systems perspective through both stages of the realization process to ensure its successful realization. A system is a combination of interacting elements organized to achieve one or more defined purposes, and a systems perspective entails focusing on any given system in its entirety, considering all the facets and all the variables involved in the entire system, rather than focusing only on the discrete parts (INCOSE, 2015).

Several methods, tools and models to support this complex realization process of the PSS have been proposed in the literature for both the design and delivery stages. The focus of this thesis is on the PSS design stage. More specifically, the focus is on improving the understanding of how designers conceptually design PSSs to support this process of designing and to improve the understanding of the effects of the support for conceptual PSS designing.

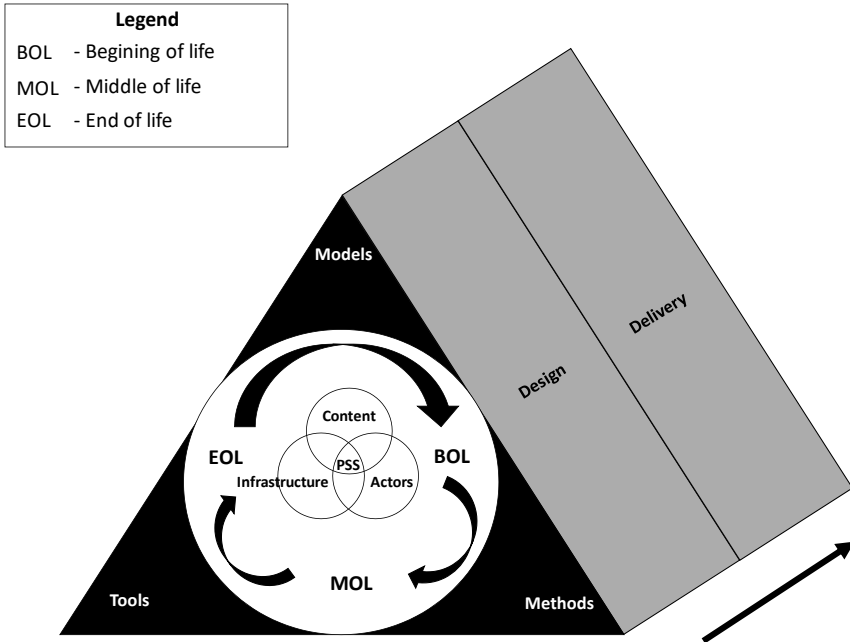


Figure 4. Representation of the conceptual framework for PSS realization (adopted and modified from Cavalieri and Pezzotta, 2012). Note: The two rectangular boxes representing the design and delivery stages are the author’s own addition to the original figure.

2.3.4 Understanding Product-Service System Designing

PSS designing is expected to vary significantly from conventional product designing as the required competence of actors involved, the macro-scale processes, and the content and context of the design of the two domains are prescriptively disparate (Morelli, 2003; Meier, Roy and Seliger, 2010; Dewberry *et al.*, 2013). From the actor’s perspective, there is a need for the extension of the designer’s competence to new logical domains, such as the social construction of technological systems, market-oriented and organizational domains (Morelli, 2003). Service designers are prescribed to be involved in the development of the product artifact, and product designers are recommended to be involved in service design (Isaksson, Larsson and Öhrwall Rönnbäck, 2009).

There are significant differences in the contents of PSSs and conventional designing both in terms of the design problems and the artifacts being designed as a

part of the solution (Dewberry *et al.*, 2013). While the macro-scale processes of product designing involve the designing and production of tangible artifacts that meet the needs of customers in use, PSS designing involves in the integration of characteristically distinct product and service artifacts from a systems perspective that together deliver expected functions, results or performance for the customers (Meier, Roy and Seliger, 2010). Morelli (2003) summarized the differences between the characteristics of products and services. A few of these differences are presented in Table 2.

Table 2. Characteristic differences of product and service artifacts (adapted from Morelli, 2003).

Characteristics of Products	Characteristics of Services
Material-intensive and tangible	Human-centric and intangible
Portable ownership	Non-portable ownership
Separation of production and consumption	Simultaneous production and consumption
Non-participation of users during production	Active participation of users during production

Despite these predicted, and in some cases, described disparities between conventional product designing and PSS designing, there are limited insights into how these differences influence the designer’s cognition. The integration of characteristically distinct products and services is expected to introduce heterogeneity, and thus, increased complexity into the cognitive design space during PSS designing. However, there is no scientific evidence supporting these claims. Substantial research effort has been expended on empirically studying and describing the cognitive nature of product designing (Dinar *et al.*, 2015; Hay *et al.*, 2017). Still, similar insights into the cognitive characteristics of PSS designing are limited.

A handful of studies have provided descriptive insights into PSS designing that are quantitative in nature. For example, Sakao, Paulsson and Mizuyama (2011) carried out descriptive studies in a laboratory setting. Through this study, they uncovered that conceptual PSS designing follows a general process of problem-solving, and lifecycle activities were identified as a centrally discussed issue during the design process. Shimomura, Nemoto and Kimita (2015) presented an approach to analyzing conceptual PSS design processes, with a visualization scheme. The insights derived from this study indicate that customer value-propositions and PSS architecture are spirally designed during the early stages of the PSS design process.

Matschewsky, Kambanou and Sakao (2018) carried out multiple descriptive case studies with two industries undergoing the transition to designing and providing PSSs. They reported qualitative insights into challenges that hinder

the transition to PSSs, such as lack of incentive structures, persistent product-centric mindset and separation of product and service design.

Although these descriptive studies provide some quantitative and qualitative insights into PSS designing, the frames of analyses used, and the results derived are mainly specific to PSS designing. Consequently, these results are not commensurable with similar insights from other domains of designing, such as product designing. This lack of commensurable insights calls for an improved scientific understanding of conceptual PSS designing.

2.3.5 Supporting Product-Service System Designing

As described in Section 1.3.2, there is a substantial body of literature that has proposed several prescriptive methods, principles or aspects to be considered during PSS designing. For example, Manzini and Vezzoli (2003) reviewed several real examples of PSSs and synthesized a strategic design approach required for designing sustainable PSSs. This strategic approach entails the configuration of stakeholders involved in the value-production system and the partnerships between producers, suppliers, customers and other societal actors. Furthermore, they suggest the need for the development of integrated systems of products, services and communication within the stakeholder networks, in line with the intended sustainability objectives.

Based on the experiences derived from simulations and partially from a case study, Morelli (2003) proposed the need for consideration of socio-cultural and user-centric perspectives during PSS designing. Isaksson, Larsson and Rönnbäck (2009), grounded on insights gathered from a literature review and multiple case studies, suggested that models, tools and simulation techniques need to represent both the properties and behavior of product and service artifacts being designed. The importance of considering the functionality of the system being designed and wider systems interaction is highlighted throughout the literature (Alonso-Rasgado, Thompson and Elfström, 2004; Maxwell, Sheate and van der Vorst, 2006).

Aurich, Fuchs and Wagenknecht (2006) highlighted the need for a lifecycle perspective and the integration of product and service elements during PSS designing. Sakao and Lindahl (2012) underscored the importance of the consideration and evaluation of customer value during PSS design and propose a prescriptive, value-based evaluation method for PSS design. The importance of achieving balance during PSS design in terms of customer value, costs and quality of products and services is also stressed in several publications (Aurich, Fuchs and Wagenknecht, 2006; Sakao and Shimomura, 2007; Pezzotta *et al.*, 2014). Despite the prevalence of several prescriptive proposals concerning PSS designing, there is a surprising lack of consolidation of this knowledge in the form of a generic and comprehensive schema that practitioners can follow

during conceptual PSS designing. Each of these prescriptive proposals captures different dimensions of PSS designing, but do not represent its essence.

There are a few design methods in the literature that aim to support PSS designing with an environmental and lifecycle-based focus. For example, Aurich, Fuchs and Wagenknecht (2006) proposed a method to support the lifecycle-oriented design of technical PSSs, which helps designers to integrate various technical services such as maintenance, retrofitting or refurbishing services to influence the ecological and economic performance of products. Geum and Park (2011) proposed a product-service blueprint approach to represent the product-service relationship, product use throughout the lifecycle and the service flow from the provider to customers, with an overarching aim of ensuring sustainable production and consumption. Sousa-Zomer and Miguel (2017), in turn, proposed a QFD-based method to support the design of sustainable PSS solutions.

Despite the availability of these useful methods, there is a lack of decision-making support for designers to quantitatively reflect on and effectively reduce the environmental impacts throughout the lifecycle of an existing offering. This information needs to be presented to designers during the early stages of conceptual design since the majority of the environmental impacts of the offering are determined during this stage (Ramani *et al.*, 2010; Lindahl, 2018).

As discussed in Section 2.2.8, LCA has the potential to provide the needed quantitative reflection of the environmental impacts of a product or service system. However, there is a lack of a systematic approach in the state of the art to incorporate the output of LCA into the conceptual design phase in the form of prioritized design requirements. Furthermore, there is no support available to prioritize the redesign of and guide the integration of product and service elements based on the results of the LCA.

This investigation of the state of the art indicates that there is a lack of a comprehensive PSS design schema to systematically guide the conceptual design process. Furthermore, it is evident that there is a lack of reflexive support for designers to reflect on the environmental impacts of an existing offering during its redesign to an environmentally benign PSS.

2.3.6 Understanding the Effects of Design Support

There are only a few studies that report scientific insights into the effects of prescriptive design support on PSS designing by comparing it with controls (i.e., design activities carried out without the use of such prescriptions). For example, Bertoni (2013) presented quantitative empirical insights into the effects of the introduction of a color-coded CAD model-based support to enhance designers' awareness during conceptual PSS designing. The results from this study indicated that the cohort of designers using the color-coded CAD model-based support better utilized available information during problem analysis and also

followed a more structured process of designing, in contrast to the cohort of designers who only used a spreadsheet-based support.

Many practitioners still follow ad-hoc approaches to designing and are wary of systematic prescriptive support procedures and methods, which in general have yet to prove their value in practice (Cross, 2006), further stressing the need for rigorous testing of the support.

“It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong.”

– Richard Feynman

Chapter 3 – Research Design

3.1 Research Philosophy

In this thesis, the author employs inductive reasoning to carry out the empirical research. An inductive approach is applied to acquire facts about the observable reality through observation or experiment (Chalmers, 1999). The observable reality in focus of this thesis is the human activity of conceptual PSS designing and the effects of prescriptive design support. Chalmers (1999) suggests that science is not merely based on factual statements regarding the observable reality, but also on the pre-existing knowledge which facilitates the formulation of the observation statements. So, the observations of conceptual PSS designing, grounded on pre-existing knowledge of the phenomenon will be used in this research to form the basis for hypothesis generation regarding the cognitive nature of conceptual PSS designing and effects of prescriptive design support.

3.2 Research Type

The research carried out in this thesis is within the emerging discipline of PSS design, which utilizes knowledge from several other established disciplines (e.g., engineering design, business management and environmental science). The thesis aims to address the lack of scientific understanding of conceptual PSS designing in the literature, the lack of effective support for conceptual PSS designing in the manufacturing industry and the lack of understanding of the effects of such support.

Furthermore, the research is carried out in close collaboration with relevant industrial actors in an effort to collaboratively address the research problems. Due to these reasons, this research can be classified as both Transdisciplinary Research Type 1, which refers to the development of a generic body of knowledge beyond any specific discipline, and Transdisciplinary Research Type 2, which refers to the temporary collaboration of academic and non-academic actors to solve specific problems (Sakao and Brambila-Macias, 2018).

Since the focus of this thesis is on understanding and supporting the conceptual designing of PSSs, it can be argued that this research is a study of processes of design and the development and application of techniques that improve the design process. This type of design research falls under the category of design praxiology, which is defined as the “study of practices and processes of design” (Cross, 2006, p. 101).

To operationalize design praxiology in the context of PSS design and to increase the scientific rigor of the research process, the design research

methodology (DRM) proposed by Blessing and Chakrabarti (2009) is used in this thesis. This framework consists of four main stages: research clarification (RC), descriptive studies (DS) – 1, prescriptive studies and descriptive studies (DS) – 2. Each of these steps is explained below in relation to the context of the thesis.

3.3 Methodological Framework – Design Research Methodology

3.3.1 Research Clarification

Following a literature analysis during the initial stage of research clarification (RC), “supporting the manufacturing industry to design REES” was set as the overarching goal of the thesis (Section 1.1). Due to its high potential for resource-efficiency and effectiveness, PSS as a design artifact was chosen as the study object of the thesis (Sections 1.1 and 1.2). The literature analysis uncovered an apparent lack of scientific understanding of conceptual PSS designing, a lack of effective support for conceptually designing PSSs and a lack of understanding of the effects of such support (Section 1.3).

The research aims and research questions were formulated (Section 1.3.3) based on the identified gaps in the literature, and from the set research questions, multiple studies were planned and spread across each of the remaining stages of the DRM. This research plan includes information regarding the research questions, DRM stages, research methods, appended research papers and the desired deliverables. An outline of this information is depicted in Figure 5.

Research Questions (RQX)	Stages of Design Research Methodology	Research Methods	Papers	Deliverables
	<pre> graph TD RC[Research clarification] --> DS1[Descriptive studies - 1] DS1 --> PS[Prescriptive studies] PS --> DS2[Descriptive studies - 2] DS2 --> RC </pre>	Literature analysis		Research plan
<ul style="list-style-type: none"> • RQ1 • RQ2 		<ul style="list-style-type: none"> • Experimental research • Literature analysis 	<ul style="list-style-type: none"> • Paper 1 • Paper 2 	<ul style="list-style-type: none"> • Empirical insights into conceptual PSS designing • Essence of prescriptive PSS design research
<ul style="list-style-type: none"> • RQ2 • RQ3 		<ul style="list-style-type: none"> • Literature synthesis • Action design research 	<ul style="list-style-type: none"> • Paper 2 • Paper 3 	<ul style="list-style-type: none"> • PSS design schema • Design navigator
<ul style="list-style-type: none"> • RQ4 		<ul style="list-style-type: none"> • Action design research • Experimental research 	<ul style="list-style-type: none"> • Paper 3 • Paper 4 	<ul style="list-style-type: none"> • Evaluation of design navigator • Empirical insights into effects of PSS design schema

Figure 5. Research Plan based on Design Research Methodology (adapted from Blessing and Chakrabarti, 2009).

Brief descriptions of the different stages of the DRM are given below. In this thesis, the DRM is not explicitly applied as given in its original format in Blessing and Chakrabarti (2009) but is contextualized to effectively address the research objectives and frame the research process. Since the research is mainly exploratory in nature, its success factor is not explicitly defined in this thesis.

3.3.2 Descriptive Studies – 1

Descriptive studies (DS) can contribute to an improved understanding of the complex activity of designing and also provide a sound basis on which to develop support (Blessing and Chakrabarti, 2009). There are two main types of DS – 1: i) a review-based DS – 1, which includes a detailed review of the literature in both the area of research and other potential areas and ii) a comprehensive DS – 1, which includes a literature review and one or more empirical studies (Blessing and Chakrabarti, 2009, p.80).

This thesis includes one comprehensive empirical and one review-based DS – 1 each, in Papers 1 and 2, respectively. The empirical research in Paper 1 will be inductive in nature. Through this research, the author aims to identify recurring patterns regarding the cognitive nature (effects) of conceptual designing from observations of product and service designers designing in an integrated approach (cause). These observations grounded on pre-existing theoretical knowledge (Section 2.3.4) will support in hypothesis generation in the author’s future research work.

3.3.3 Prescriptive Studies

The prescriptive studies (PS) stage involves the development of prescriptive support for designing, based on the insights derived from DS – 1 and the knowledge gaps and research opportunities identified in the RC stage. The prescriptive support can include strategies, methodologies, procedures, methods, techniques, software, tools and guidelines (Blessing and Chakrabarti, 2009).

In this thesis, the PS stage includes two separate prescriptive proposals. One is an initial PS, which only includes a description of the support (Blessing and Chakrabarti, 2009, p.143) based on the insights of the review-based DS – 1 and is documented in Paper 2. A comprehensive PS is also proposed, which is a support that is realised to such an extent that its core functionality can be evaluated for its potential to fulfil the purpose for which it was developed (Blessing and Chakrabarti, 2009, p.144). This PS is documented in Paper 3 and is developed to address an important practice-oriented knowledge gap uncovered in the literature analysis during the RC in Section 1.3.2.

3.3.4 Descriptive Study – 2

Blessing and Chakrabarti (2009) stated that the descriptive study (DS) – 2 stage mainly includes empirical studies that are used to evaluate application and

impacts of the design support that has been developed in the PS stage. In this thesis, DS – 2 includes two empirical studies that evaluate such effects of the two prescriptive proposals developed in the PS stage. The introduction of a design support might create new situations that did not exist before and might lead to many unexpected events after (Blessing and Chakrabarti, 2009). It is important to observe, measure and report these effects. The two PS proposals are subjected to descriptive studies and documented in Papers 3 and 4. The empirical research in Paper 4 will also be inductive in nature. Through this research, the author aims to observe the influence of the intervention of prescriptive design schema (cause) on the cognitive nature of conceptual PSS designing (effects). These observations grounded on pre-existing theoretical knowledge will drive the author's future research.

Different research methods and data collection techniques are used in this methodology to collect empirical and theoretical data for the various stages. These methods are briefly described in the following sections.

3.4 Research Methods

3.4.1 Overview

There are many research methods that can be utilized to provide insights into designing, such as case studies, observations, protocol studies, simulation trials, theoretical analysis and reflections (Cross, 2006). In this thesis, several of these research methods are utilized across the different stages of the applied DRM.

3.4.2 Literature Analysis and Synthesis

Literature analysis and review is fundamental to any research, as it is critical to establish a background and context before undertaking a study (Marshall and Rossman, 1995). It is a crucial part of any research since it allows the researcher to map relevant established intellectual information of the phenomenon being studied and further enhance the knowledge base (Tranfield, Denyer and Smart, 2003). This research method is the major source of information for the research clarification and DS – 1 stage. Webster and Watson (2002) suggest that literature reviews should be concept centric. The insights need to be logically structured around the central topics under investigation. The utility of the insights derived from such a review will be high since it will leave room for a potential synthesis (ibid). Thus, the literature analysis and review undertaken is structured around the central topic of this thesis, PSS design.

In the research clarification stage, the state of the art of PSS design research is diligently explored to uncover knowledge gaps and to formulate research aims and research questions. Literature analysis and review are also used to establish the theoretical framework of this thesis. It is further utilized in Paper 2 to extract

the essence of PSS design research through a meta-synthesis of relevant literature in the state of the art. Sandelowski, Docherty and Emden (1997) suggested that such a synthesis of existing knowledge is crucial, as it can potentially contribute to the achievement of analytical goals and also increase the generalizability of qualitative research.

Meta-synthesis can be utilized to capture theories, ideas, narratives, generalizations or interpretations elicited from the integration or comparisons of qualitative studies centered around a topic of interest (Sandelowski, Docherty and Emden, 1997). This type of synthesis is ideal for capturing the essence of prescriptive PSS design literature, which is primarily qualitative in nature. It will promote the consolidation of the knowledge gathered in the state of the art, which is currently missing and is crucial to guide future research in PSS design.

Furthermore, the synthesis of extant knowledge can also be crucial from a practice point of view (Sandelowski, Docherty and Emden, 1997), as it can be utilized to effectively guide the practitioners. Thus, the insights gathered from a meta-synthesis of PSS design literature is consolidated in the form of a systematic procedure for conceptually designing PSSs. Therefore, literature analysis and synthesis are utilized to answer RQ2 and is primarily documented in Paper 2. It is also the source of the theoretical foundation of this thesis and the rest of the papers.

3.4.3 Experimental Research

The experimental research method is applied to answer RQ1 and RQ4 in the DS-1 and DS-2 stages of this thesis, respectively. Experimental research is undertaken when a researcher aims to trace cause and effect relationships between defined variables (Williamson, 2002, p. 125). A variable is an element or factor under investigation in the experiment. There are two types of variables: i) the independent variable, which is the factor manipulated by the researcher to see what impact it has on other variable(s), and ii) the dependent or effect variable, which is the factor measured to determine how it has responded to a particular manipulation (Williamson, 2002, p. 127). Generally, in experimental research, there are two types of groups, the control group and the experimental group.

Experimental groups are generally exposed to a defined manipulation or some condition of the independent variable, while control groups are not exposed to any manipulation and are measured on the dependent variable (Williamson, 2002, p.129). A well-controlled experiment with limited intervening variables and well-defined experimental and control groups is referred to as a “true experiment” (Williamson, 2002, p.130), which is generally high in validity. Prior to conducting true experiments, pre-experiments are generally carried out, which bear some similarities to the former but lack many controls. One example of a pre-experimental research design is a static group comparison in which subjects are divided into groups on the basis of whether or not they

possess a specific characteristic under study, and where observations are recorded and subsequently compared (Williamson, 2002, p.140).

In this thesis, a combination of static group comparison and true experiment is used to form the basis of future research. Static group comparison as a part of pre-experiments is applied to form the basis to answer RQ1 in order to provide initial scientific insights into the cognitive nature of conceptual PSS designing carried out by experienced practitioners. True experimental design is also applied to form the basis to answer RQ4 to provide initial scientific insights into the effects of a prescriptive design support methodology on conceptual PSS designing.

Experiments in laboratory settings were preferred over case studies in industrial settings, primarily because it is impractical to shadow the participants in their real-life work settings. Furthermore, PSS designing requires simultaneous and unrestricted collaboration between product and service designers (Meier, Roy and Seliger, 2010); however, in practice, they usually operate in silos and carry out their tasks in sequence (Matschewsky, Kambanou and Sakao, 2018).

3.4.4 Action Design Research

Action research (AR) can be considered a hermeneutical approach of human actions and social practices, in which the researcher searches for knowledge as an observer and simultaneously creates practical benefits to the collaborating practitioner (Williamson, 2002). Action design research (ADR) (Sein *et al.*, 2011), a derivative of AR, is primarily used in the discipline of information science and is adopted and modified in this thesis to address RQ3 in Paper 3. Sein *et al.* (2011) describe ADR as “a research method for generating prescriptive design knowledge through building and evaluating IT artifacts in an organizational setting”. In the context of this thesis, ADR is used to generate prescriptive design knowledge by supporting the conceptual designing and evaluation of a PSS-based REES in an industrial case.

ADR addresses the following two challenges: i) addressing a problem situation within an organizational setting by intervening and evaluating and ii) constructing and evaluating an artifact that addresses the identified challenges (Sein *et al.*, 2011). Sein *et al.* (2011) further elaborate that the response to these two challenges often results in a method that focuses on the building, intervention and evaluation of the artifact. Such a result should not only reflect the theoretical precursors and intent of the researchers but also the influence of the end users and ongoing use in a specific context (Sein *et al.*, 2011).

One of the aims of this thesis is to support the designing of PSS-based REES in industrial settings. The answer to RQ3 intends to operationalize this aim by supporting the designing of such an artifact in a specific industrial case, and subsequently generating prescriptive knowledge in the form of a design method that can be applied to other similar contexts in industry. This prescriptive

method not only reflects relevant theoretical precursors but also the context of the practitioners who use the method. It also considers the situation of the end-users who use the artifact and of its resulting environmental impacts.

Due to these reasons, ADR is chosen as the appropriate method to answer RQ3 and is primarily utilized in Paper 3 in an implicit fashion. AR has been previously applied in multiple domains of design, such as in product design, to develop environments that support the collaboration of multi-disciplinary teams in product lifecycle engineering (Mejía, López and Molina, 2007), and in service design to enhance value co-creation in social innovation initiatives (Yang and Sung, 2016).

3.5 Data Collection Techniques

3.5.1 Protocol Analysis

Protocol analysis is the main data collection technique employed for the collection and analysis of data for the experimental research. More specifically, it is utilized in Papers 1 and 4 to collect and analyze cognitive data in the form of think-aloud protocols during conceptual PSS designing in laboratory settings. Protocol analysis was initially described by Ericsson and Simon (1993) and further developed by van Someren et al. (1994). The think-aloud protocol is referred to as the process of speaking out one's thought sequences while carrying out a defined activity, i.e., designing (van Someren, Barnard and Sandberg, 1994). The verbal thought sequences generated from the think-aloud protocols are collected as valid sources of data on cognition in the rigorous method of protocol analysis.

Protocol analysis is a widely used and validated method for the elicitation of verbal data on cognition (Ericsson and Simon, 1993; van Someren, Barnard and Sandberg, 1994). This method was extended and transformed into a useful tool for design research by Gero and Mc Neill (1998) to support the development of an understanding of how designers design.

Various studies have utilized this approach to generate and test hypotheses that have improved the understanding of design activities (Mc Neill, Gero and Warren, 1998; Purcell and Gero, 1998; Kannengiesser and Gero, 2015; Hay *et al.*, 2017; Kan and Gero, 2017). In this thesis, coding schemes based on the FBS ontology and a scheme for systems hierarchy are used to analyze the protocol data.

3.5.2 Retrospective Technique – Document Analysis

Retrospective techniques (Blessing and Chakrabarti, 2009), such as document analysis, are used to collect some background data during the initial stages of ADR at the industrial case company. Document analysis is a systematic procedure for reviewing or evaluating documents which involves the examination and

interpretation of data in order to elicit meanings, gain understanding and develop empirical knowledge (Bowen, 2009).

Previous studies can also be a source of data for document analysis, which requires the researcher to rely on the description and interpretation of the data rather than having only the raw data as a basis for analysis (ibid). According to Bowen (2009), the analytic procedure of document analysis entails finding, selecting, appraising and synthesizing relevant data contained in the documents.

3.5.3 Focus Groups

The focus group is used as a data collection technique for the industrial case application of the developed prescriptive design support method in DS – 2 stage of this thesis to collect data for the ADR. A focus group is “a carefully planned discussion designed to obtain perceptions on a defined area of interest in a permissive, non-threatening environment” (Krueger, 1994, p.6).

It is used to collect qualitative data and is appropriate when the goal is to investigate how the participants regard an experience, idea or event (ibid). It can be utilized to stimulate new ideas and creative concepts and to diagnose the potential problems of new services or products, generating impressions of products, programs, services or other objects of interest (Stewart and Shamdasani, 1990).

3.5.4 Semi-Structured interviews

The semi-structured interview is used in the DS – 2 stage of this thesis to collect data for the ADR. It was chosen as the data collection technique to collect feedback from the participants of the focus group during the industrial case application of the developed design support method, as it can offer detail, depth and an insider perspective to the issue being investigated (Leech, 2002). Furthermore, it allows the respondents to take the role of experts of the phenomenon being investigated and to inform the research (ibid).

3.6 Research Quality Measures

3.6.1 Overview

As revealed earlier, this thesis includes both quantitative and qualitative types of research, and different measures are taken in the thesis to ensure high quality for both.

3.6.2 Measures for Quantitative Studies

Quantitative or “positivistic” studies are mainly appraised by the levels of validity and reliability of the research methods and results. Validity in quantitative research determines whether the means of measurement are accurate and if they actually measure what they are intended to measure (Golafshani, 2003).

Reliability in quantitative research is determined by the replicability of the results (Golafshani, 2003). These two measures are utilized in this thesis to appraise the rigor of the methods and the results presented in Papers 1 and 4 of the DS – 1 and DS – 2 stages, respectively.

3.6.3 Measures for Qualitative Studies

There are three main types of validity in qualitative studies: i) descriptive validity, which refers to the factual accuracy of the qualitative information as reported by the researcher; ii) interpretive validity, which refers to the degree to which the research participants' viewpoints, thoughts, intentions and experiences are accurately understood and reported by the researcher; and iii) theoretical validity, which refers to the degree that a theory or theoretical explanation developed from a research study fits the data (Johnson, 1997). Only descriptive and interpretive validity of the qualitative results, published in Paper 3 and included in the DS – 2 stage, are measured in the thesis. Theoretical validity is not considered here, as the results of the assessment do not have much relevance to theory, but only to practice.

“Nature uses only the longest threads to weave her patterns, so that each small piece of her fabric reveals the organization of the entire tapestry.”

— Richard Feynman

Chapter 4 – Results and Discussions

4.1 Preliminary Insights into the Cognitive Nature of Conceptual PSS Designing

4.1.1 Overview

The research presented in this section is taken from Paper 1. It provides initial descriptive and quantitative insights into conceptual PSS designing. This research is a part of the DS – 1 stage of the thesis and will form the basis to answer RQ1: *What is the cognitive nature of conceptual PSS designing performed by experienced practitioners?* The paper presents the empirical results of protocol analysis of five sets of pre-experiments (design sessions) involving five pairs of experienced practitioners each, from industry, carrying out a pre-defined design task in a laboratory setting.

The pre-defined design task was to conceptually design a natural, resource-efficient PSS, based on an existing product and related services. The existing product was an office-use coffee machine and its related services, such as maintenance, repair and provision of required consumables. Each pair included one product designer and one service designer. The participants were asked to engage in the think-aloud protocol during the task. These protocols were subjected to both audio and video recording.

There are three levels of analysis of the coded protocol data. The first level provides quantitative insight into the cognitive effort expended by the participants of experiments on the various design issues. The second level of analysis provides insights into the distribution of cognitive effort applied by the participants on the syntactic design processes. In the third level of analysis, the results of distribution of cognitive effort spent on design issues collected from this study are subjected to static group comparison with similar data extracted from other published studies involving different cohorts conceptually designing products.

4.1.2 Results

As described earlier, the protocol data was analyzed using a scheme based on the FBS ontology. Table 3 presents an excerpt of this analyzed data in order to contextualize the FBS coding scheme.

Table 3. Excerpt from the segmented protocols (translated into English from Swedish). Taken from Paper 1 (Neramballi, Sakao and Gero, 2018).

Designer	Segment	Code
A	(Writes)	D
A	Service report	S
B	When it is used	Be
A	And what it is used for I saw that it was	F
B	Which I interpret as each one has his own card	Be
B	And then you go and take coffee	Bs

Note: F refers to Function, D to Design Description, S to Structure, Be to Behavior Expected and Bs to Behavior of Structure (see Section 2.1.3 for more details).

Distribution of cognitive effort on design issues

The overall distributions of cognitive effort on various design issues defined by the FBS ontology for each of the five design sessions, the average distribution across the five sessions and the coefficient of variation for each are presented in Table 4. The results indicate that behavior (considering both Be and Bs) is the most discussed design issue during conceptual PSS designing, which constitutes almost half of the total average of cognitive effort expended by the practitioners over the five design sessions. Behavior is closely followed by F and S.

Table 4. The design issue distribution in each of the five sessions, mean over the five sessions and respective standard deviations are expressed as percentages and co-efficient of variation as ratios. Taken from Paper 1 (Neramballi, Sakao and Gero, 2018).

	S1	S2	S3	S4	S5	Mean	σ	CV
Function (F)	20.5	26.2	26.2	18.0	23.7	22.9	3.23	0.14
Expected behaviour (Be)	18.2	21.6	15.1	17.5	25.4	19.5	3.58	0.18
Behaviour of structure (Bs)	33.3	26.3	24.2	30.8	22.8	27.4	3.97	0.14
Structure (S)	19.4	20.1	28.7	19.6	23.3	22.2	3.53	0.17
Design description (D)	8.4	5.5	5.0	13.8	4.7	7.4	3.42	0.45

Note: “Sn” refers to “Session n”, σ to standard deviation and CV to Coefficient of variation.

Distribution of cognitive effort on syntactic design processes

The distribution of the syntactic design processes defined by the FBS ontology for each of the five design sessions, the mean across five sessions, respective standard deviations and the respective co-efficient of variation are shown in

Table 5. This distribution is given in terms of the percentage of the ratio of occurrence of each process over that of all the eight processes.

Table 5. The syntactic design process distributions in each of the five sessions, mean over the five sessions and respective standard deviations, expressed as percentages and co-efficient of variation as ratios. Taken from Paper 1 (Neramballi, Sakao and Gero, 2018).

	S1	S2	S3	S4	S5	Mean	σ	CV
F→Be	14.6	9.8	5.8	11.5	13.8	11.1	3.14	0.28
Be→S	9.9	8.3	6.1	9.9	10.9	9.0	1.68	0.18
S→Bs	17.0	13.2	16.0	18.5	12.9	15.5	2.17	0.13
Be–Bs	20.4	22.8	18.6	21.8	22.0	21.1	1.47	0.06
S→D	6.8	3.4	4.9	5.8	2.9	4.7	1.45	0.30
S→S	18.3	24.6	33.4	16.0	17.7	22.0	6.40	0.29
S→Be	7.7	8.9	7.0	8.2	9.9	8.3	0.99	0.11
S→F	5.3	8.9	8.1	8.2	9.9	8.0	1.53	0.18

Note: “Sn” refers to “Session n”, σ to standard deviation and CV to Coefficient of variation. F→Be: Formulation, Be→S: Synthesis, S→Bs: Analysis, Be – Bs: Evaluation, S→D: Documentation, S→S: Reformulation 1, S→Be: Reformulation 2, S→F: Reformulation 3.

The results in Table 5 indicate that during conceptual PSS designing, designers expend their maximum cognitive effort on Reformulation 1, which includes transitions from S to S and on Evaluation, which include transitions between Be and Bs.

Comparative analysis of conceptual PSS designing and conceptual product designing

As revealed in Chapter 2, several past studies have utilized protocol analysis and FBS ontology to study product designing. The results of these studies are commensurable with results of other studies that have used the same method and frame of analysis, even though the design object under study in each are characteristically different.

In Paper 1, the author and colleagues have compared several such published studies involving different cohorts, conceptually designing different products in different settings. More specifically, the cognitive effort expended by designers on various design issues during the conceptual designing of products is compared with that of conceptual PSS designing as reported in this study.

In Table 6, the mean distributions of cognitive effort on different design issues extracted from multiple studies of product design are compared to that of PSS design, which is extracted from this study.

Table 6. Average design issue distributions from multiple studies of product design as compared to this study (of PSS design), expressed as percentages. Taken from Paper 1 (Neramballi, Sakao and Gero, 2018).

Study	R	F	Be	Bs	S	D
This Study	0.4	22.9	19.5	27.4	22.2	7.4
Mean of other existing product design studies	2.4	3.3	15.3	27.4	34.4	15.1

The results in Table 6 indicate that the cognitive effort on F is significantly more dominant in conceptual PSS designing than in conceptual product designing. In contrast, the cognitive effort on S is more dominant in conceptual product designing than in conceptual PSS designing.

4.1.3 Research Quality Appraisal

The above-described results were drawn from only five pre-experiments (measured only one type of cohort). Each pre-experiment included one pair of participants. This cohort size is not enough to draw statistically reliable insights but is indeed sufficient to form the basis for future research. The protocol data was coded using a scheme based on the widely used FBS ontology by two independent coders and arbitrated by a third expert.

Even though there is some degree of subjectivity in the analysis, the coders had an average inter-coder agreement percentage of 71%, which points towards an acceptable level of validity. The standard deviations and coefficients of variations of the results of the distribution of cognitive effort on design issues and design processes are relatively low. However, due to the small sample size, these results have limited statistical reliability.

Furthermore, the results of the pre-experiments of this study were compared against equivalent data sets of product designers, conceptually designing a product, collected from other extant laboratory studies. However, there is a lack of control in this pre-experimental design as each of these cohorts in these studies is characteristically distinct, since the participants include a mix of non-experts such as junior and senior engineering graduates, professionals and experts. Even though some regularities are observed in the comparative data, the validity and reliability of such comparisons are limited. Thus, these insights are just utilized to form the basis for the author’s future research, which will eventually answer RQ1.

4.1.4 Discussion

The literature analysis described in Section 2.3.4 reveals that during PSS designing, the characteristically distinct, tangible products and intangible services are prescribed to be integrated in a systemic manner. Furthermore, there are several

other prescribed disparities between conventional product designing and PSS designing. The results presented above provide some initial scientific insights into the unique cognitive nature of conceptual PSS designing, thus forming the basis to answer RQ1. The results indicate that, on average, there seems to be significantly more focus on function as a design issue during conceptual PSS designing than during product designing.

The higher focus on function could be attributed to the extended cognitive design space that is observed during PSS designing. This extended design space allows designers to design concepts of solutions that deliver functional results, in contrast to conventional product designing, which mainly focuses on designing material-intensive products. This argument can be further strengthened by the relatively higher focus on structure evident during conceptual product designing.

Furthermore, PSS designers expend around half of their total share of cognitive effort on the design issue behavior. This effort on behavior during PSS designing appears to be slightly more than the effort on behavior during product designing. This slight difference in the average cognitive effort on behavior can potentially be attributed to the increased heterogeneity, and thus complexity in the PSS design space, introduced by the interactions of the characteristically distinct products and services (see Section 2.3.4).

The increased complexity in the PSS design space can also potentially explain the relatively high focus on the design process evaluation, which are transitions between Be and Bs. These results provide a basis to support the claims in the literature concerning the unique nature of conceptual PSS designing and the need for dedicated design approaches and prescriptive support.

4.1.5 Reflections Regarding Research Method – Protocol Studies with Pre-Experimental Design

Wheelwright and Clark (1992) had highlighted the importance of and previously prevalent lack of cross-functional integration between design and manufacturing activities in industry. This lack of cross-functional integration has since been addressed with considerable advances in manufacturing practice.

Even though the state of the art highlights the need for a similar integration of product and service design activities for the effective design of PSSs, a persistent lack of such cross-functional integration in industry has been reported (see Section 2.3.4). This lack of ideal conditions for PSS designing in industry prompted the need for carrying out controlled protocol studies of the conceptual design activity of experienced practitioners in a laboratory setting. More specifically, five pre-experiments in a controlled laboratory setting were carried out. These pre-experiments were exploratory in nature and will form the basis to carry out true experiments in a laboratory setting in the author's future work.

Ball and Christensen (2018) suggested that laboratory studies of the design practice have limitations in comparison to other forms of research approaches, such as ethnographic studies of “designing in the wild or real-world design context”. These limitations can include the lack of consideration of several variables prevalent in the real-world context of design.

Despite these limitations, the results derived from laboratory studies can potentially provide valuable insights into the design activity (Cash, Hicks and Culley, 2013), which may not be possible to obtain in industrial settings. This argument is echoed by Cross, as he suggests that protocol analysis “is the most likely method (perhaps the only method) to bring out into the open the somewhat mysterious cognitive abilities of designers” (Cross, 2006, p.77). Moreover, the cohort involved in these studies comprised experienced practitioners with around nine years of experience in industry. Studies of such experts are crucial to providing insights into design expertise (Cross, 2006).

4.2 Essence of Extant Prescriptive Support for PSS Design

4.2.1 Overview

The research presented in this section is taken from Paper 2. This research is qualitative in nature and is a part of both DS – 1 and PS stage of the thesis. It was carried out to address the lack of consolidation of extant prescriptive knowledge regarding conceptual PSS designing. This consolidation will answer RQ2: *What is the essence of existing prescriptive PSS design knowledge?* To answer this research question, the authors initially analyzed and described the extant prescriptive PSS design knowledge in the literature in the DS – 1 stage. Subsequently, the insights were synthesized and consolidated in the form of a prescriptive design support schema for conceptual PSS designing in the PS stage.

The DS – 1 stage involved the meta-analysis of existing literature reviews of PSS design to distill the essence of most recurring elements, themes and narratives across the state of the art. In the PS stage, a meta-synthesis of the distilled essence of PSS design principles and support methods and tools was carried out. The insights gathered from this synthesis were then consolidated into the mould of PBSA (Pahl and Beitz, 2007). PBSA is one of the most widely used generic and systematic design approaches to conventional designing. This consolidation resulted in a design schema, which is essentially a structured outline of relevant issues to be considered during conceptual PSS designing.

While the conventional approaches might support practitioners to design product elements and services activities disparately, the tight integration of product and service elements requires these elements to be designed concurrently. Consequently, a dedicated schema is deemed necessary for conceptual PSS designing, due to its unique characteristics in terms of macro-scale dimensions (see Section 2.3.4) and its cognitive nature (see Section 4.1). This schema

is expected to provide necessary guidance on an abstract level to designers by highlighting the relevant issues specific to the PSS design domain, and by efficiently structuring their cognitive design processes.

4.2.2 Results

The results of the meta-analysis and subsequent synthesis of literature are consolidated in the form of a structured design schema. The structure of this schema is based on the widely used systematic approach to conventional designing by Pahl and Beitz (2007) and is adapted to the PSS design context informed by the literature synthesis. This prescriptive schema, depicted in Figure 6, is recommended to be used by designers as an instructional guide during conceptual PSS designing, in a sequence of ten steps with multiple iterations wherever required.

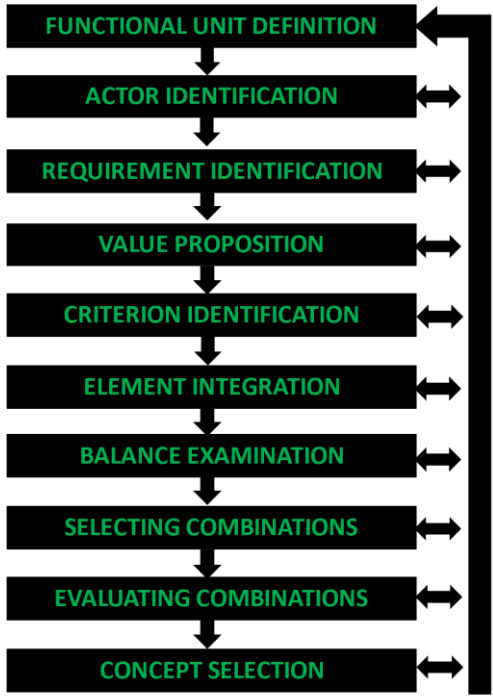


Figure 6. Prescriptive PSS Design Schema, from Paper 2 (Sakao and Neramballi, 2020).

Recurring aspects uncovered by the literature synthesis includes an emphasis on designing functionality or result-oriented design solutions with reduced environmental impacts. Designers are recommended to initially define a functional unit for the PSS design solution to address this important aspect. In this context,

the functional unit represents a measure of the teleological aspects of the PSS being designed in terms of the expected performance or results, rather than the specific contents of the PSS.

Other facets of PSS design include the identification and consideration of actor or stakeholder requirements across the lifecycle of the solution, value proposition, conceptualization of product and service design elements, integration and combination of these elements, optimization of balance during product and service element integration with a systems and lifecycle perspective.

4.2.3 Discussion

The literature analysis in Section 2.3.4 revealed that there are significant disparities in terms of design content and macro-scale dimensions of conventional designing and PSS designing, respectively. The answer to RQ1 also revealed potential indications of disparities between the two domains in terms of the micro-scaled, cognitive nature of the conceptual design process. Consequently, conventional design practices may not be suitable for designing PSSs.

The above-presented generic PSS design schema represents the essence of the existing prescriptive PSS design knowledge, which is essentially different compared to that of conventional product design knowledge. This unified schema is also expected to contribute towards the development of a common knowledge schema for computational PSS knowledge acquisition support systems that focus on declarative and procedural PSS knowledge, as the different existing support systems currently utilize disparate knowledge schemata (Vasantha, Roy and Corney, 2015).

This prescriptive schema is expected to support the designers with PSS domain specific knowledge during conceptual designing and thus is expected to improve the design process. This type of domain specific prescription is considered to be crucial to support practitioners who are not experienced in PSS design, since problem-solvers with limited experience in a specific problem area are expected to require support tailored to that domain, rather than support composed of generic problem solving strategies (Sweller, Van Merriënboer and Paas, 1998). Past research indicates that designers following methodically flexible procedures tend to generate good solutions (Cross, 2006). Consequently, designers are not prescribed to strictly go through each step of the presented schema sequentially but are recommended to iterate as required in a flexible manner.

Clayton, Backhouse and Dani (2012) previously carried out a similar literature analysis of PSS design approaches and synthesized a generic PSS design approach. However, this approach is for the overall development of PSSs. Unlike the PSS design schema presented in Paper 2, the synthesized PSS design approach by Clayton, Backhouse and Dani (2012) does not outline the relevant

granular aspects for the PSS designers to consider during the conceptual design phase. The effects of the PSS design schema on conceptual PSS designing, reflections regarding research quality and research design are investigated and discussed in Section 4.4.

4.3 Decision-Making Support for Conceptual PSS Designing to Reduce Environmental Impacts – Lifecycle-Oriented Function Deployment

4.3.1 Overview

The research documented in this section is taken from Paper 3 and is a part of the PS stage of the thesis. The results of the literature analysis described in Section 2.3.4 and the answer to RQ1 described in Section 4.1 point towards the need for dedicated design support methods and approaches to designing environmentally benign PSSs. Even though there are several design methods that support such activities, a lack of contextual support to design environmentally benign PSSs was identified. The research documented in this section aims to address this practice-oriented knowledge gap by answering the following research question: *How can the decision-making of designers be contextually supported during conceptual PSS designing to reduce the environmental impacts?*

To answer this RQ, ADR is utilized to develop and evaluate a contextual and prescriptive design navigator named lifecycle-oriented function deployment (LFD) in an industrial case. The part of Paper 3 described in this section only regards the development and application of LFD in a real industrial case.

4.3.2 Results

Overview of lifecycle oriented function deployment

LFD builds on LCA and QFD, two of the most widely used tools and methods to support designing. Initially, a practice-inspired research problem was identified through literature analysis. These analyses revealed that currently, there is no systematic and contextual support available for practitioners to translate and feed the output of the LCA of an existing offering into the early stages of its conceptual redesign to a PSS.

Quantitative reflection on the environmental impacts of an existing design object is crucial to guide effective design interventions and integration of product and service elements, which can potentially reduce the environmental impacts of the PSS being designed. LFD was developed to address this lack of support for the manufacturing industry and was subsequently tested in an industrial case application.

LFD has four phases. Initially, in Phase 0, a novel systematic procedure is presented for converting LCA output into prioritized environmental-oriented design requirements, and to normalize it with prioritized customer-oriented design requirements. In Phases 1 and 2, the prioritized design requirements are fed into two QFD-based matrices that can guide the design/redesign effort of designers by identifying hotspots of design characteristics and components of both products and services. Hotspots refer to specific product and service characteristics and components that relatively have the highest relative influence on the prioritized design requirements.

Lastly, in Phase 3, a novel procedure is proposed that supports the designers to identify hotspots of product and service characteristics, which, when integrated, have relatively the highest relative influence on the prioritized design requirements. Designers focus on the identified hotspots in order to develop PSS concepts that can subsequently address the prioritized design requirements. An overview of this design method is presented in Figure 7.

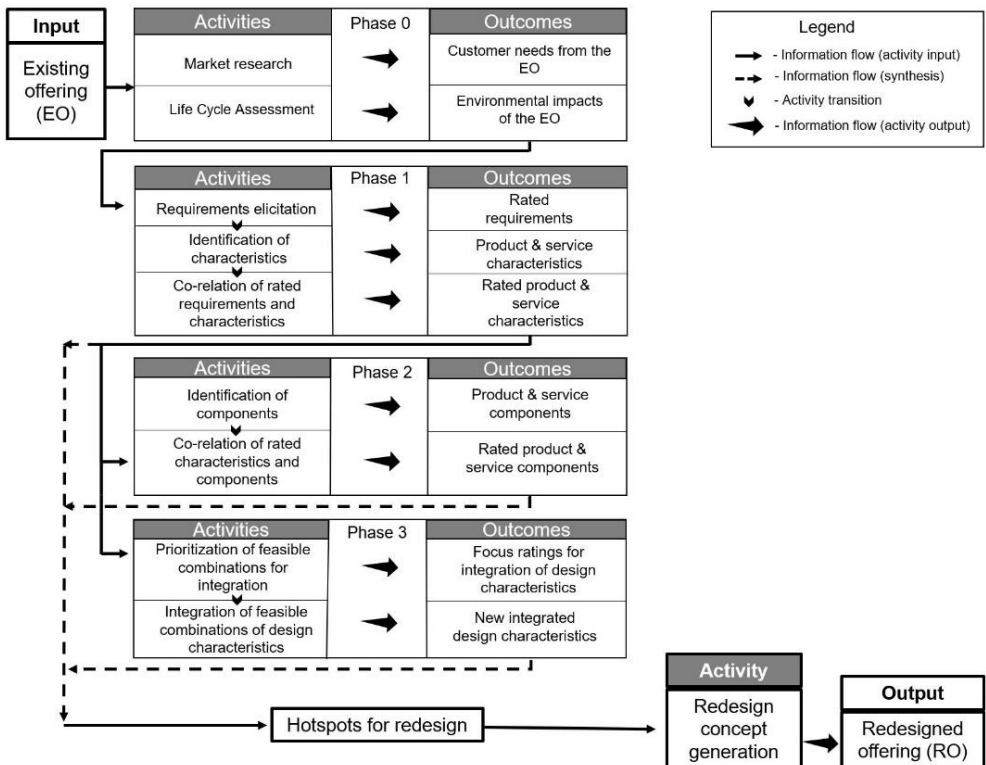


Figure 7. Overview of lifecycle-oriented function deployment. Taken from Paper 3 (Neramballi et al., under review).

Overview of industrial application

LFD was applied in a real industrial setting in order to evaluate its effects and usefulness. The industry in focus is a large-scale manufacturer of incontinence products, based in Sweden. Initially, document and lifecycle data analysis were carried out to collect relevant data on a product-centric existing offering (EO) that was being conceptually redesigned to a PSS based REES in the collaborating industry.

This EO is a portfolio of incontinence products. Initially, documented information regarding past interviews and survey data of market research of the EO was analyzed. This information was provided to the authors by the collaborating industry. This analysis provided insights into the customer needs and expectations from the EO, which is manufactured and provided to the market by the collaborating industry.

Subsequently, lifecycle data analysis was carried out, which provided quantitative insights into the environmental impacts of the same EO. This data was extracted from an earlier research work of two of the co-authors of Paper 3, who conducted a comprehensive LCA on the same product system (Willskytt and Tillman, 2019). The data collected from these sources were fed into Phase 0 of LFD by the authors and were converted into prioritized design requirements.

These prioritized design requirements were subsequently verified by the practitioners of the collaborating industry in a focus group, carried out in a workshop setting. This conceptual design workshop included the following key personnel of the collaborating industry: a senior product developer, a senior service/market developer and a senior environmental manager. It was organized in the premises of the headquarters of the collaborating industry in Sweden. The workshop also involved three researchers, including the author of this thesis.

Initially, the researchers presented and described LFD to the other participants in the workshop. The participants were then left to carry out the analysis of the EO in focus and simultaneously carry out the QFD-based exercise of Phase 1 using digital spreadsheets. The semi-quantitative data generated by the practitioners during the QFD-based exercise was recorded digitally. Questions and doubts raised by the practitioners concerning LFD were clarified by the researchers. This workshop lasted for around five hours, and the discussions carried out by the practitioners were recorded in audio format.

Based on the audio recording of the discussions of the workshop participants, the researchers completed Phases 2 and 3 in digital format at a later date. These results were then sent to the workshop participants for their expert review and relevant corrections. After their review, an online video conference was held with the participants of the workshop to further discuss the details of their review. The reviewed information was utilized by the authors to generate concepts for a redesigned offering (RO). These concepts and the utility of LFD were then

evaluated using a simulated LCA and in a semi-structured interview with the workshop participants in the DS – 2 stage of the thesis.

4.3.3 Discussion

Schönheyder and Nordby (2018) summarized three distinct approaches to design method development, as found in the literature: 1) constructing a new method from a theoretical framework, 2) adopting two or more methods to construct a new method and 3) adapting and evolving an existing method. LFD was developed using the 2nd and 3rd approaches detailed above. QFD and LCA, two of the most widely used methods in both practice and academia, are combined, adapted and evolved to structure a new method to support designers during the design of PSS-based REES.

QFD has been previously used to translate environmental requirements derived from LCA to support the eco-design of products (Sakao, 2007), and also to support PSS designing (e.g., Sakao *et al.*, 2009); moreover, it is reported to be one of the most adopted methods in the PSS engineering literature (Cavalieri and Pezzotta, 2012). However, before LFD, there was no systematic procedure available in the state of the art to convert LCA results into prioritized environmentally-oriented design requirements and to normalize it with prioritized customer-oriented design requirements, to be fed as the input to QFD for PSS. Furthermore, LFD presents a novel approach to prioritize the integration of product and service design characteristics, based on the results of the QFD and LCA. This prescriptive support contributes to the advancement of the eco-design research body and also provides effective support for designers. The evaluation of LFD and the outcome of its industrial application, reflections regarding research quality and research design are investigated and discussed in Section 4.4.

4.4 Empirical Insights into the Effects of Prescriptive Support for Conceptually Designing PSSs

4.4.1 Overview

The research presented in this section is a part of the DS – 2 stage of the thesis, which was carried out to address a crucial knowledge gap concerning the effects of prescriptive support on conceptual PSS designing. The results are both qualitative and quantitative in nature and are derived from both Papers 3 and 4.

The results form the basis to answer the following RQ4: *What are the effects of the intervention of prescriptive support during conceptual PSS designing?* The answer to this RQ includes the results of the evaluation of LFD, a prescriptive design navigator, which is described in detail in Paper 3. The answer also includes the results of evaluation of the effects of the prescriptive schema for conceptual PSS designing, which is described in detail in Paper 2.

4.4.2 Results Regarding Evaluation of the Industrial Application of Lifecycle Function Deployment

Results of simulated LCA

The concepts generated using the outcomes of the industrial application of LFD were evaluated through a simulated LCA by manipulating the lifecycle data of the EO, based on the suggested conceptual design changes. The generated concepts for the RO were quite similar to the ones suggested and assessed by a previous study (Willskytt and Tillman, 2019) performed by two of the co-authors of Paper 3.

Thus, the LCA data for the assessment of the new concepts were taken from this previous work and modified accordingly to simulate and assess the potential environmental impacts of the concepts for RO. These concepts were derived as an outcome of the application of the design navigator. The normalized impact assessment results for the specific impact categories that were identified in Phase 0 of LFD application for the EO and the simulated results for the RO are illustrated in Figure 8.

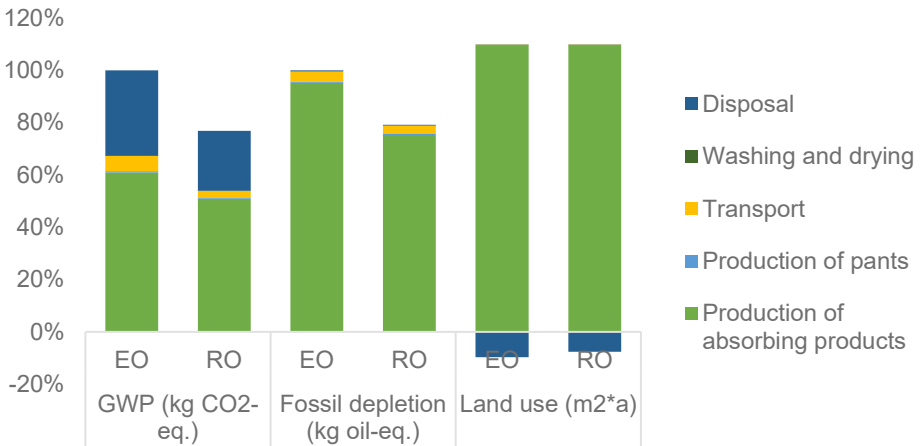


Figure 8. Normalized impact assessment result for the selected impact categories global warming potential (GWP), fossil resource depletion and land use for RO (redesigned offering) compared with EO (existing offering). Taken from Paper 3 (Neramballi et al., under review).

The LCA results indicate that the potential environmental impacts (mainly for the impact categories global warming potential and fossil resource depletion) of the concepts of RO (experimental data) are relatively less compared to that of EO (control data).

Results of the semi-structured interview

The concepts of RO were presented to the personnel of the industrial case company who participated in the conceptual design workshop. They reviewed the concepts and suggested relevant changes. Later, a semi-structured interview was carried out with these participants to evaluate LFD. The interview provided insights into the viability of the generated concepts of RO and the utility of LFD.

The interviewees indicated that some of the concepts for redesign were viable in practice and would be considered for further development. They considered the rest of the concepts to be relevant and acknowledged them as steps in the right direction, in line with their ambitions to reduce the environmental impacts of EO.

The interviewees also highlighted several benefits of LFD. They indicated that it provided them a structured approach to their design activities, to incorporate environmental considerations right from the early stages of design/redesign, to systematically design and integrate services and to involve cross-functional actors in the early stages of design. They also highlighted the potential of LFD as a pedagogic tool.

4.4.3 Discussion Regarding Evaluation of the Industrial Application of Lifecycle Function Deployment

The presented design navigator, LFD, provides reflexive and contextual support to practitioners in considering the quantitative environmental impacts of an EO being redesigned into an environmentally benign PSS. The effects and utility of LFD were investigated through the ADR approach with an industrial case application, using simulated LCA and a semi-structured interview. As an outcome, the industrial case company received useful concepts for the redesign of its offering and also a structured and contextual approach to conceptually design such offerings. This prescriptive approach is potentially applicable to other similar industrial settings.

The comparative simulated LCA of the EO and RO provided initial quantitative insights into the potential effects of LFD on the environmental performance of the conceptual design outcomes. The semi-structured interview provided some initial qualitative insights into the utility and benefits of LFD from the user point of view. These descriptive insights provide reflectiveness into prescriptive PSS design research.

4.4.4 Research Quality Appraisal Regarding Evaluation of the Industrial Application of Lifecycle Function Deployment

The following measures were taken to ensure both descriptive and interpretive validity of the qualitative results derived from the evaluation of LFD in the DS – 2 stage of the thesis. Both the workshops and interviews were audio-recorded.

Further, the semi-quantitative information collected in the focus group-based conceptual design workshop was recorded digitally. Other information analyzed and qualitatively interpreted by the researchers after the workshop was consistently reported back to the participants. This was done to obtain participant feedback to ensure that the analyzed information accurately represented their viewpoints (Johnson, 1997).

If the qualitative reports did not accurately represent the viewpoints of the participants, they were requested to make suitable changes. Furthermore, multiple researchers were involved in both the workshop and the semi-structured interview to ensure investigator triangulation (Johnson, 1997). Investigator triangulation was done to make sure that the qualitative data was interpreted consistently from multiple viewpoints. The results presented in this work are limited to a single case study, and multiple case studies are required to increase the reliability of the findings. Furthermore, the reliability and validity of the findings would have been increased if the suggested concepts were developed further and subjected to more rigorous evaluations.

4.4.5 Reflections Regarding Research Method – Action Design Research

LFD was developed to provide contextual decision-making support to practitioners during the design of environmentally benign PSSs. The ADR approach was utilized to apply and evaluate the developed LFD in the industrial case company, in collaboration with the practitioners of the company. This approach allowed the researchers to investigate and collaboratively address the practitioner's problem scenario. According to Sein *et al.* (2011), action design researchers should generate prescriptive knowledge that can be applied to generic classes of problems that are extrapolated from case-specific, contextual problems.

The problem scenario of the industrial case company was defined by a lack of a systematic approach i) to incorporate environmental considerations into the early stages of its design activities, ii) to systematically design and integrate services into its product-centric offerings that could potentially reduce the overall environmental impacts, and iii) to support cross-functional integration of relevant actors during the early stages of design. Some of these problems are reported to be prevalent across other industries seeking to transition towards the design and provision of environmentally benign PSSs (Matschewsky, Kambanou and Sakao, 2018).

While carrying out ADR, Sein *et al.* (2011) advocated for the development of design artifacts that are ingrained in theory. In the context of this industrial case application, the concepts developed as an outcome of LFD are ingrained in the prescriptive theories of the PSS design artifact. Furthermore, ADR should consider the mutual influences of the organizational context on the design

artifact and the mutually influential roles of practitioners and researchers during the process of ADR. The generated artifact should be concurrently evaluated.

ADR should also facilitate reflection and learning for all the actors involved. Some of these learning outcomes can then be generalized and disseminated within the research and practice communities. These principles of ADR (Sein *et al.*, 2011) were implicitly applied during the application and evaluation of LFD and during the conceptual design of a PSS-based REES in the industrial case company. This research method was utilized as it allows researchers to study real industrial problems that are relevant on a generic scale, to introduce changes and potential benefits to the collaborating industry and to derive prescriptions that are applicable on a generic scale.

4.4.6 Results Regarding Effects of the Prescriptive Design Schema for Conceptual PSS Designing

Experimental design

A true experiment was carried out to investigate the effects of the schema for conceptual PSS designing (the outcome of RQ2), provided to PSS designers. The experiment included two pairs of experienced practitioners from industry, carrying out a pre-defined design task in a controlled laboratory setting. The pre-defined design task was to conceptually design a natural resource-efficient PSS, based on an existing product system and related services.

The existing product was an office-use coffee machine and its related services such as maintenance, repair and provision of required consumables. Each pair included one product designer and one service designer. One pair of the participants was considered as the experimental group. This group was provided with and trained in the use of the conceptual PSS design schema, developed and prescribed in Paper 2 (see Section 4.2). The other pair was classified as the control group and was not provided with any such support.

All the participants were asked to engage in the think-aloud protocol during the task. These protocols were subjected to both audio and video recording. These sets of protocol data were subsequently coded using the scheme based on the FBS ontology and a scheme based on systems hierarchy, by two independent coders and arbitrated by an expert. The results indicate differences in the cognitive effort expended by both the control and experimental group on various design issues, syntactic design processes and different levels of systems hierarchy.

Distribution of cognitive effort on design issues

The two independent coders had an average inter-coder agreement percentage of 81%, with a standard deviation of 5.5%, for coding based on the FBS ontology over the control and experimental groups. There was a substantial increase in the effort on D. Without considering the effort spent by designers on D, the results indicate that there is an increase in the cognitive effort on R by around 2

times, on F by around 1.33 times and S by around 1.25 times. The highest decrease in cognitive effort appears to be on the design issue Bs, with around 0.58 times as that of the control group. The results are presented in detail in Table 7.

Table 7. Design issue distributions for the control and experimental groups. Taken from Paper 4 (Neramballi, Sakao and Gero, 2019).

Design Issues	G1 without “D” [%]	G2 without “D” [%]	Ratio (G2/G1)
R	1	2	2.00
F	24	32	1.33
Be	22	21	0.95
Bs	34	20	0.58
S	20	25	1.25

Note: R – Requirements, F – Function, D – Design Description, S – Structure, Be – Behavior Expected and Bs – Behavior of Structure (see Section 2.1.3 for more details).

Distribution of cognitive effort on design process distribution

The results of the distribution of cognitive effort on syntactic design processes over control and experimental groups are given in Table 8. These results indicate that the highest increase in cognitive effort in the experimental group is on the syntactic design process Reformulation 2, closely followed by Reformulation 1 and Documentation. Interestingly, the cognitive effort on Evaluation seems to have been halved in the experimental group.

Table 8. Syntactic design process distribution. Taken from Paper 4 (Neramballi, Sakao and Gero, 2019).

	Control group (G1) [%]	Experimental group (G2) %	Ratio (G2/G1)
F→Be: Formulation	10.8	13.8	1.27
Be→S: Synthesis	9.0	9.4	1.04
S→Bs: Analysis	12.2	10.1	0.82
Be – Bs: Evaluation	36.9	18.8	0.50
S→D: Documentation	8.1	13.0	1.60
S→S: Reformulation 1	8.1	13.0	1.60
S→Be: Reformulation 2	5.9	10.1	1.71
S→F: Reformulation 3	9.0	11.6	1.28

Distribution of cognitive effort on different levels of systems hierarchy

The two coders had an average inter-coder agreement ratio of around 87%, with a standard deviation of 3.4% over the control and experiment groups. The

distribution of the designers’ cognitive effort on the three levels of system hierarchy in both the control and experimental group is given in Table 9.

Table 9. Distribution of the design criteria of the systems coding scheme. Taken from Paper 4 (Neramballi, Sakao and Gero, 2019).

	Control group (G1) [%]	Experimental group (G2) [%]	Ratio (G2/G1)
Discrete (D)	54	37	0.65
Interactions (I)	38	36	0.94
Systems (S)	8	27	3.37

The results indicate that with the introduction of the schema, there is more than a three-fold increase in the cognitive effort on the systems level.

4.4.7 Discussion Regarding Effects of the Prescriptive Design Schema for Conceptual PSS Designing

The introduction of the prescriptive schema for PSS designing appears to have influenced the distribution of cognitive effort of the designers in the experimental group. The highest increase in cognitive effort in terms of design issues seems to be on F, Reformulation 2, in terms of design processes and on the systems perspective in terms of problem abstraction. These increases in the cognitive effort on the design issue function and systems perspective were expected, due to the strong emphasis on functionality and the systems perspective in the prescriptive PSS design literature (see Section 2.3.4).

Interestingly, there seems to be a substantial reduction in the cognitive effort on evaluation. These results indicate that the prescriptive schema could indeed influence the designers’ cognition, even though it is not possible to draw conclusions from this study alone, due to the limited cohort size.

4.4.8 Research Quality Appraisal Regarding Effects of the Prescriptive Design Schema for Conceptual PSS Designing

Two independent coders and a third expert arbitrator were used to code the data using commensurable and widely applied frameworks. Even though the coding introduces a certain degree of subjectivity to the analysis, the independent coders had a relatively high inter-coder agreement ratio, which points towards acceptable levels of validity. However, the cohort size of this true experiment is not sufficient to draw statistically reliable insights.

More research with larger cohort sizes is necessary to derive relatively valid and statistically reliable conclusions. The results of this study indicate that the effects of such a prescriptive support for conceptual PSS designing can be tested

quantitatively, and thus form the basis for the author's future research, which will eventually answer RQ4.

4.4.9 Reflections Regarding Research Method – Protocol Studies with True Experimental Design

An exploratory protocol study with a true experimental design was carried out to investigate the potential effects of the intervention of the PSS design schema. Such an experimental setting was chosen as it allows the researcher to trace the cause and effect relationship of a certain phenomenon, simulated in a controlled laboratory setting (Williamson, 2002). The objective of Paper 4 was to exploratively investigate the effects of the cause (the prescriptive PSS design schema) on the designers' cognition during conceptual PSS designing.

The author acknowledges that even though laboratory studies provide insights into design cognition with relatively high levels of validity, there are several limitations, such as a lack of external generalizability. This lack of external generalizability could be due to the controlled exclusion of several intervening variables that are prevalent in the real-world context of design. To address this issue, mixed-method approaches, such as the combination of practice, intermediary and laboratory studies, can be carried out (Cash, Hicks and Culley, 2013).

4.5 Meta-Analysis of Scientific Contributions

The answer to RQ1 provided some early insights into the cognitive nature of conceptual PSS designing and its potential differences with conceptual product designing. These empirical insights are the outcomes of laboratory studies of experienced practitioners conceptually designing PSS. Such insights into the cognitive nature of designing are crucial to developing scientifically rigorous models and theories of the design activity (Cross, 2006; Dorst, 2008; Gero, 2010). Even though the results do not have statistical significance, they appear to support the widely claimed need in the literature for dedicated prescriptive support to conceptual PSS designing. In order to address this need for dedicated support, two prescriptions specific to conceptual PSS designing were developed.

The answer to RQ2 consolidated the essence of existing prescriptive PSS design principles, methods and tools. The outcome of this consolidation was a PSS design schema, which is a structured outline of procedural aspects to be considered during conceptual PSS designing. This prescriptive support is expected to provide guidance to designers in a flexible yet methodical way to consider all relevant issues specific to the PSS design domain. It is also expected to influence their problem-solving strategies and cognitive processes. This consolidated schema can potentially be used as a basis for further research to create a unified ontology which is essential to develop dedicated design methods and knowledge support systems for PSS designing. This type of unified schema and

computational knowledge support systems were identified as important future research trajectories in a review by Vasantha, Roy and Corney (2015).

The answer to RQ3 developed a design navigator named as LFD, which provides contextual decision-making support to the conceptual designing of environmentally benign PSSs. This type of support was deemed to be necessary by Ullman (2002) for conventional designing, as he claimed, “often designers do whatever is easiest, not what will lead to the best decision...Much time is wasted making poor decisions”. Even though this issue might have been adequately addressed by advanced knowledge and manufacturing practices of conventional designing, it is still relevant for PSS-based REES designing. LFD is expected to improve the efficacy of PSS design in terms of the environmental impacts and customer satisfaction of the design outcomes. While the outcome of RQ2 provides support on an abstract and generic level in terms of how to conceptually design PSS-based REES, the outcome of RQ3 provides guidance to PSS designers on a more granular and contextual level.

In order to address the lack of reflectiveness in terms of the scientific effects of prescriptive PSS design research, the answer to RQ4 evaluated the two prescriptions (the outcomes of RQ2 and RQ3). Potentially positive effects of LFD on the environmental impacts of the conceptual design outcomes and benefits for the method users were observed and described. The potential effects of the PSS design schema on the cognition of the designers during conceptual PSS designing were also observed and described. This type of rigorous testing of prescriptive support is crucial to advance the knowledge of design research (Dorst, 2008). The above-described relationships between the outcomes of the four research questions are depicted in Figure 9.

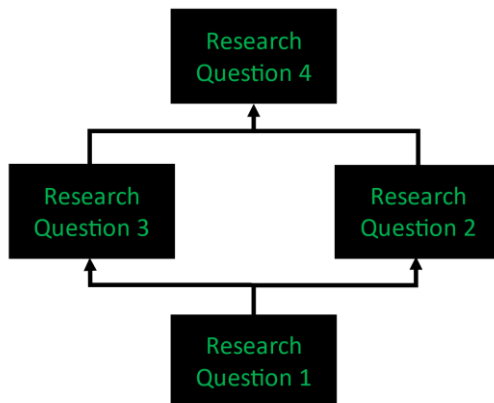


Figure 9. Schematic representation of the inter-relationships of the outcomes of the research questions (Author’s own).

4.6 Practical Implications

The outcome of RQ1 reaffirms the widely claimed unique nature of conceptual PSS designing. This finding has implications for both practice and pedagogy, as industries seeking to transition to PSSs and pedagogy for designing PSS based REES might need to incorporate dedicated approaches to PSS designing. The two prescriptions, which are outcomes of RQ2 and RQ3, provide both abstract and granular support, respectively, for conceptual PSS designing.

“To raise new questions, new possibilities, to regard old problems from a new angle, requires creative imagination and marks real advance in science.”

– Albert Einstein

Chapter 5 – Conclusions and Future Research

5.1 Conclusions

This licentiate thesis is an attempt to form the basis to increase the understanding of and to support the cognitive processes of conceptual PSS designing. This aim is addressed by answering the following research questions (RQs):

RQ1 What is the cognitive nature of conceptual PSS designing performed by experienced practitioners?

The descriptive and quantitative results of Paper 1 (briefly documented in Section 4.1) indicate that experienced practitioners appear to expend the majority share of their cognitive effort on the design issue behavior (expected behavior and behavior of structure) and on the syntactic design processes Reformulation 1 and Evaluation.

The practitioners appear to expend more cognitive effort on the design issue function during conceptual PSS designing than during conceptual product designing. Conversely, the practitioners appear to expend less cognitive effort on the design issue structure during conceptual PSS designing than during conceptual product designing.

Although these results do not yet have statistical significance, they appear to support the claims of the unique cognitive nature of conceptual PSS designing. These insights strengthen the arguments for dedicated support and approaches to conceptual PSS designing. The answer to this RQ forms the basis for the author's future research.

RQ2 What is the essence of existing prescriptive PSS design knowledge?

The prescriptive and qualitative results of Paper 2 (briefly documented in Section 4.2) show the essence of existing prescriptive PSS design knowledge, consolidated in the form of a conceptual PSS design schema. This schema outlines the following sequence of steps specific to the PSS design domain: identification of a functional unit, actor identification, requirement identification, value proposition, criterion identification, element integration, balance examination, selecting combinations, evaluating combinations and concept selection. These steps are recommended to be carried out during conceptual PSS designing in a methodical yet flexible manner.

RQ3 How can the decision-making of designers be contextually supported during conceptual PSS designing to reduce the environmental impacts?

The prescriptive and qualitative results of Paper 3 (briefly documented in Section 4.3) present LFD and its industrial application. LFD is a prescriptive design navigator which supports designers to conceptually design environmentally benign PSSs, based on the quantitative information of the environmental impacts of a previous generation design solution. The key procedures of LFD include i) a systematic procedure to translate the output of the LCA and market research of an existing solution into relatively prioritized redesign requirements, ii) a QFD for a PSS-based procedure to prioritize the redesign of specific product and/or service design parameters based on the relatively prioritized redesign requirements, and iii) a novel procedure to prioritize the integration of product and service design characteristics that together have high influence on prioritized redesign requirements.

RQ4 What are the effects of the interventions of prescriptive support on conceptual PSS designing?

The descriptive and quantitative results of Paper 4 (briefly presented in Section 4.4.2 – 4.4.5) pave the way forward for the author’s future research by showing preliminary indications of certain effects of the PSS design schema on the cognition of experienced practitioners conceptually designing PSSs. The results indicate that the cognitive effort on behaviour seems to have been reduced upon the intervention of the schema.

While the designers’ cognitive effort on syntactic design process Reformulation 2 almost doubles, the effort on Evaluation is halved. Further, the results also seem to indicate that the application of a systems perspective (focus on the system being designed) seems to have tripled upon the intervention of the schema, accompanied by a sharp decline in a reductionist perspective (focus on the discrete elements being designed). Even though conclusions cannot be drawn from this study due to the limited cohort size, it forms the basis for the authors’ future research, which will contribute to theory building.

The descriptive, semi-quantitative and qualitative results of Paper 4 (briefly presented in Sections 4.4.6 – 4.4.9) evaluate the utility of LFD in terms of the potential environmental impacts of the generated concepts of PSS and the usefulness for the support users. Environmental impacts of the concepts of the redesigned offering using LFD seems to be relatively lower than that of the existing offering. The practitioners who used LFD verified the viability of a few concepts and discussed potential challenges in further developing the rest of the concepts.

To summarize, this licentiate thesis forms the basis to develop the future research work of the author, which aims to scientifically understand and support the conceptual designing of PSS-based REES. The contributions of this future

work are expected to support the PSS design research community and the manufacturing industry in the transition towards a CE. The planned trajectories of this future research work of the author are described below.

5.2 Future Research Trajectories

This licentiate thesis lays the groundwork for the author's future research work. The descriptive study documented in appended Paper 1 was exploratory in nature. It provided initial empirical insights into the cognitive nature of conceptual PSS designing and indications of its potential differences to conceptual product designing. Since the level of control and size of the cohort used in this pre-experimental study were limited, the statistical reliability and validity of the results are also limited.

The future research work of the author will focus on generating statistically reliable and valid results with a true experimental design. These experiments will involve two cohorts of experienced practitioners. One cohort will be the control group, which will mainly include several pairs of expert product designers, conceptually designing a product in a laboratory setting. The other cohort will be the experimental group, which will include several pairs of experienced practitioners, with one expert product designer and one expert service designer in each pair, conceptually designing a natural, resource-efficient PSS in a laboratory setting.

Protocol analyses will be conducted to collect the data from these experiments. Subsequently, the data will be analysed with scientifically rigorous frameworks. The insights derived from the analyses of these two sets of cohorts will then be compared with each other to characterise the cognitive nature of conceptual PSS designing. The insights derived from these comparisons will be utilized as a basis to generate scientifically rigorous theories and explanatory models. These theories are expected to answer RQ1 comprehensively.

The above-described future work, which will form the answer to RQ1, might be utilized by the author to develop dedicated and effective prescriptive support for conceptual PSS designing. To do so, the PSS design schema, extracted from the appended Paper 2 and described as an outcome of RQ2 of this thesis, will initially be rigorously tested in the future research work of the author. The groundwork for this future research has been laid out in the answer to RQ4, extracted from appended Paper 4. A true experimental design will be used in a similar fashion to the research described in Paper 4. This experimental design will include two sets of cohorts, conceptually designing a PSS in a laboratory setting.

The control group will include several pairs of experienced practitioners, conceptually designing a PSS, without the support of the prescriptive PSS design schema. The experimental group will include several pairs of experienced practitioners, conceptually designing a PSS, with the support of the prescriptive

PSS design schema. Protocol analyses will be carried out to collect the data on the expert practitioners' cognition, and scientifically rigorous frameworks will be utilized to analyse the data. The insights from these analyses of the two sets of cohorts will be compared to provide scientifically rigorous, empirical insights into the effects of the PSS design schema on the cognitive nature of conceptual PSS designing. These insights will be utilized to develop scientifically rigorous explanatory models and theories, which will comprehensively answer RQ4.

The above-described future work, expected to form the answers to RQ1 and RQ4, might be utilized in an additional future work of the author, which will serve as a basis to reflexively improve the PSS design schema. This potentially improved PSS design schema is planned to be utilized to facilitate learning among experienced practitioners in industry, in an effort to support them in the effective design of PSS-based REES. Longitudinal studies, using the ADR approach, are expected to be carried out to operationalize this future work. In this thesis, the ADR approach was utilized implicitly to answer RQ3. It will serve as a methodological inspiration to effectively design the planned longitudinal studies.

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Why should you read this book?

Unsustainable industrial practices are the “patient-zeroes” of the “pandemic” of environmental challenges faced by humanity. The activity of design can be effectively used to develop potential “cures” in the form of resource-efficient and effective industrial solutions, to overcome this looming pandemic. This book provides initial insights into how such solutions are designed by experienced designers, and presents tools to support their endeavor.

Who is this book for?

This book is intended for change agents such as researchers, designers in industry and students who aim to improve the resource efficiency and effectiveness of industrial design solutions.

What will you get from this book?

- Empirical insights into how experienced practitioners from industry cognitively design resource-efficient and effective solutions, and how it potentially varies from conventional designing.
- A design schema that outlines the procedural aspects to consider during the conceptual design of resource-efficient and effective solutions.
- A design navigator that provides contextual and granular support to enhance decision-making during such a design activity.
- Empirical insights into the effects of the proposed prescriptive design support on the cognition and efficacy of the design activity.