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Framing a generic process for capital goods manufacturing companies

Sarancic, David

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David Sarancic

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PhD Thesis

David Sarancic

September 2023

Technical University of Denmark

Department of Civil and Mechanical Engineering

Section of Design for Sustainability

Early-stage design of Product-Service Systems (PSS) for sustainability: Framing a generic process for capital goods manufacturing companies

PhD Thesis

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Author: David Sarancic

Email: dasar@dtu.dk; david.sarancic@gmail.com

Main supervisor:

Tim C. McAloone, Professor

Co-supervisor:

Daniela C.A. Pigosso, Associate Professor

Technical University of Denmark

DTU Construct

Department of Civil and Mechanical Engineering

Section of Design for Sustainability

Building 402

2800 Kgs. Lyngby

Denmark

Abstract

Product-service systems (PSS) have returned to the forefront of industry's attention once again after the subsided enthusiasm in the last decade, as one of the pivotal enablers of a circular economy – a situation which is mirrored in the academic literature. The now more mature nature of PSS challenges the prevalent conviction that the expression "sustainable manufacturing" is an oxymoron with its potential to decouple economic growth and value creation from resource consumption.

Manufacturing companies are the drivers of PSS design and implementation in practice, but despite this role and a few successful examples, PSS implementation remains limited in industry. Many barriers continue to pose themselves for companies that recognise the potential to implement PSS, such as a lack of understanding of customer needs, technological limitations, and internal resistance to change. These persevere due to the complexity and multifacetedness that PSS design embodies, hence, hindering a widespread rollout of PSS and the harvest of the triple-bottom-line sustainability benefits that PSS is estimated to potentially deliver.

PSS design in manufacturing companies does not necessarily yield more sustainable offerings by default, let alone by intuitive or ad hoc approaches. There is a need for solid support, which is currently missing in both academic literature and as an industry standard. The support is most needed in terms of a systematised framework that can guide the PSS design processes and aid decision-making, especially during the early-stage design, where the most influential decisions on the success of future offerings are made.

The research was conducted in close collaboration with the primary case company Aasted ApS, a capital goods manufacturing company in the food processing machinery industry. Several other capital goods manufacturing companies and academic experts were engaged in the co-creation and/or evaluation of the proposed support for PSS design.

Four principal results are brought forward in this PhD thesis. First, an overview of the literature, as well as an in-depth empirical investigation concerning the drivers and barriers for PSS design in manufacturing companies. Second, a comprehensive overview of early-stage PSS design approaches with a focus on sustainability, and their characteristics described in the state-of-the-art literature. This overview served as the basis to develop a structured generic process model (GPM) for early-stage sustainable PSS design that unified learnings from 96 identified approaches and was evaluated in multiple case studies. Third, the consolidated guidelines to support the implementation and instantiation of the GPM in capital goods manufacturing companies. Fourth, a comprehensive PSS concept sustainability screening tool rigorously theoretically and empirically developed and evaluated through action research in the primary case company, as well as in a follow-up case study.

To arrive at these results and devise the necessary and suitable support, the Design Research Methodology (DRM) approach was employed in this research, with the objective of developing a systematic framework to support (equipment) manufacturing companies in the early-stage PSS design and evaluation for sustainability. The methodology encompassed three main cycles to describe the current situation, and then prescribe and evaluate the support to fulfil the research objective, based on the mixture of methods (e.g., systematic literature review, action research, case studies).

The in-depth evaluations of the proposed supports with the primary case company and other companies demonstrated that their application was successful in supporting early-stage PSS design for sustainability. Based on the use of the instantiated GPM and the screening tool, the primary case company was able to design and select the most promising PSS concept and initiate pilot project implementation.

"Sustainable manufacturing is an oxymoron" – Yvon Chouinard, the founder of Patagonia

Preface and Acknowledgments

Pursuing a PhD has been both a challenging and rewarding experience. The journey of conducting research and contributing to the advancement of knowledge in the sustainability-related field invoked in me a similar duality of feelings. On one hand, I had a sense of satisfaction in knowing that my work may even slightly contribute to addressing such a pressing global issue. On the other hand, the enormity of the problem and the disappointingly slow progress in worldwide sustainability-related developments had a daunting effect on me. Despite these ambiguities, I reflect on my PhD journey as being enjoyable and well-worth undertaking primarily due to the passionate and remarkable people I had by my side along the way.

My gratitude goes to my supervisor, Tim McAloone, for managing to make me leave your office inspired after every meeting. You have this fascinating ability to always see the bigger picture and provide a fresh perspective, with a perfect blend of professional and personal approaches. I am honoured to have had a shot at being a "little Tim" for a while. I am also grateful to my co-supervisor, Daniela Pigosso, for all the encouragement and for always being available for a discussion. You have this ability to quickly introduce structure to all things unstructured, and instantly elevate the relevance and rigour of our research. The dedication of both of my supervisors to sustainability and teaching will eternally be my inspiration to strive forward and upward, even in the light of adversity. I feel lucky to have had to opportunity to learn and grow in the environment you created with the perfect blend of abilities and skills that you embody together.

During the PhD project, I felt exceptionally privileged to be a part of the Manufacturing Academy of Denmark (MADE). I would like to thank all industrial partners involved in this research programme. I have experienced a great will to collaborate and exchange learnings in the network of researchers that MADE established. It was both humbling and flattering to get recognition for my efforts by receiving one of Otto Mønsteds Fond's MADE prizes for excellence in research. I also had a much-appreciated opportunity to join forces with adept consultants from FORCE Technology, primarily Michele Colli, to whom I owe gratitude for many valuable perspectives.

My thanks and admiration go to the Aasted family and Aasted's management for always supporting my work. Special thanks to Morten Pilnov for giving me the opportunity, Carsten Lundberg for holding my hand in the early days, Henrik Heitmann Jensen for many inspiring discussions and for sponsoring my project, Christian Ingemann Hansen for opening the doors of the Aftersales Department and providing me with pragmatical insights, Martin Løkkegaard for all things MADE and data, and all the great people at Aasted.

I thank professors Giuditta Pezzotta and Fabiana Pirola for kindly hosting me and supporting my research during my stay at the University of Bergamo. I extend my appreciation to all CELS' members.

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Lastly, I would like to thank my wonderful family. First, to my parents Snježana and Jelisije, and my siblings Sara Laura and Nenad, for standing by my side in any circumstances and motivating me to pursue my dreams, even from a distance. Then, to my Nikolina. Your continuous wholehearted emotional support and encouragement. Thank you for bearing the long working hours and for celebrating all the little wins with me. Thank you to both our families and close friends for supporting me all the way.

Thesis Overview

This PhD thesis is assembled in a paper-based style, with the papers embedded as appendices. It is structured into five main chapters:

Chapter 1 introduces the theoretical and empirical context and motivation for the research (Sections 1 and 1.3, respectively), the research scope and gaps (Section 1.4), the overall objective and principal hypothesis (Section 1.5), and the corresponding research questions (Section 1.5).

Chapter 2 elaborates on the research methodology and the research structure utilised to answer the research questions and obtain the key results (section 2.1). Further, it presents the methods applied throughout the research (section 2.2).

Chapter 3 presents the summary of the research findings. The results are reported in full in the appended publications indicated at the beginning of each of the four sections (3.1-3.4) which follow the cycles of the research methodology.

Chapter 4 describes how the individual results make up the systematic framework for early-stage PSS design for sustainability, which then fulfils the overall objective of this PhD (Section 4.14.1). Then, a reflection on the research findings is presented (Section 4.2), followed by the relation of the key results to each research question (Section 4.3). Finally, the limitations of this research (Section 4.4) and the suggestions for future research (Section 4.5) are brought forward.

Chapter 5 draws overall conclusions based on academic and industrial contributions (section 5) and closes with final remarks (section 5.2).

An overview of the Appended Publications and Supplementary Publications resulting from this research is available on the next page.

The Appended Publications consist of three journal papers and two conference papers that document the majority of academic results presented in this thesis and they can be found at the end of this thesis.

The Supplementary Publications are not in the appendix of this thesis, but they can be accessed through the indicated DOI or links and will be referenced in the thesis to support the findings, when relevant.

List of Appended Publications (AP)

Publication 1 (Conference paper) – Drivers and barriers in practice

Sarancic, D., Pigosso, D.C.A., and McAloone, T.C. (2021), “Sustainability driven Product-Service Systems development: a case study in a capital goods manufacturing company”, *KES-SDM 2021 Conference*, Vol. 262 SIST, Springer Singapore, pp. 1–11. Doi:10.1007/978-981-16-6128-0_1.

Publication 2 (Journal paper) – Development of the Generic Process Model (GPM)

Sarancic, D., Pigosso, D.C.A., Pezzotta, G., Pirola, F. and McAloone, T.C. (2023), “Designing sustainable product-service systems: A generic process model for the early stages”, Sustainable Production and Consumption, Elsevier, Vol. 36, pp. 397–414. Doi:10.1016/j.spc.2023.01.020.

Publication 3 (Journal paper) – Evaluation and instantiation of the Generic Process Model (GPM)

Sarancic, D., Pigosso, D.C.A., and McAloone, T.C. (2023), “Evaluation and instantiation of a generic process model for early-stage sustainable Product-Service System (PSS) design within three manufacturing companies”, *(Manuscript under review at the Journal of Cleaner Production).*

Publication 4 (Journal Paper) – Development of the Business, Environmental and Social Screening Tool for Product-Service Systems (BESST).

Sarancic, D., Pigosso, D.C.A., Colli, M., and McAloone, T.C. (2022), “Towards a novel Business, Environmental and Social Screening Tool for Product-Service Systems (BESST PSS) design”, *Sustainable Production and Consumption*, Elsevier, Vol. 33, pp. 454–465. Doi:10.1016/j.spc.2022.07.022.

Publication 5 (Conference paper) – BESST case study

Sarancic, D., Metic, J., Pigosso, D.C.A. and McAloone, T.C. (2023), “Impacts, synergies, and rebound effects arising in combinations of Product-Service Systems (PSS) and circularity strategies”, Procedia CIRP, Vol. 116, pp. 546–551. Doi.org/10.1016/j.procir.2023.02.092.

List of Supplementary Publications (not included in the thesis)

Publication 6 (Conference paper) – Drivers and barriers in literature

Sarancic, D., Pigosso, D.C.A., and McAloone, T.C. (2021), "Investigating Drivers and Barriers for the Development of Product-Service Systems in Capital Goods Manufacturing Companies", *Proceedings of the Design Society*, Gothenburg, Sweden, Vol. 1 No. August, pp. 1927–1936. Doi:10.1017/pds.2021.454.

Publication 7 (Conference paper) – Initial instantiation study of the GPM

Sarancic, D., Sánchez Díez, A., Pigosso, D.C.A. and McAloone, T.C. (2023), "Instantiating a generic process model for early-stage Product-Service System (PSS) design in two capital goods manufacturing companies", *Proceedings of the Design Society*, Cambridge University Press, Vol. 3, pp. 2325–2334. doi:10.1017/PDS.2023.233.

Publication 8 (Conference paper) – PSS pilot projects

Sarancic, D., Pigosso, D.C.A., and McAloone, T.C. (2022), "Designing Industrial Product-Service System (PSS) Pilot Projects in Manufacturing Companies: A Proposed Process for Product and Customer Selection", *Proceedings of the Design Society*, Cambridge University Press, Vol. 2, pp. 1119–1128. Doi:10.1017/pds.2022.114.

Publication 9 (Conference paper) – Thesis summary

Sarancic, D., Pigosso, D.C.A., and McAloone, T.C. (2023), "Systematic framework for early-stage sustainable product-service system (PSS) design in capital goods manufacturing companies", *Proceedings of the 4th Symposium on Circular Economy and Sustainability*, 19-21 June 2023, Heraklion, Greece.

Abbreviations and Acronyms

AP	Appended publication
AR	Action research
BESST	Business, environmental, and social screening tool
BM	Business model
BoL	Beginning-of-life
CE	Circular economy
C1	Cycle 1
C2	Cycle 2
C3	Cycle 3
CGMC	Capital goods manufacturing company
DRM	Design Research Methodology
DS-I	Descriptive study I
DS-II	Descriptive study II
EoU	End-of-use
ETO	Engineering-to-order
GPM	Generic process model
HVAC	Heating, ventilation, and air conditioning
MADE	Manufacturing Academy of Denmark
MoL	Middle-of-life
OEE	Overall equipment effectiveness
OEM	Original equipment manufacturer
PS	Prescriptive study
PSS	Product-service system
RC	Research clarification
RQ	Research question
SLR	Systematic literature review
TBL	Triple-bottom-line

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1 Introduction

The first chapter presents the overview of the theoretical (section 1.1) and empirical context (section 1.2) and the motivation for the research presented in this PhD thesis. The chapter continues to explain the research gaps (section 1.3) and present the objective and hypothesis that directed this research (section 1.4). Finally, the research questions examined in this thesis are formulated (section 1.5).

1.1 Theoretical context and motivation

As the world continues to grapple with the challenges of climate change and environmental degradation (Figueres *et al.*, 2017), there is a growing urgency to find ways to reduce our impact on the planet (Williams *et al.*, 2021). Nations across the globe are increasingly recognising the pronounced need to contribute to the Sustainable Development Goals (SDGs) and remain within the safe and just Earth system boundaries (Allen *et al.*, 2018; Rockström *et al.*, 2009, 2023). Manufacturing companies, as major resource and energy consumers and contributors to climate change problems (Zhang *et al.*, 2018), are likewise embracing and exploiting the promises of business development oriented towards sustainability (Breuer *et al.*, 2018; Dhanda and Shrotryia, 2021) and pledging to ambitious corporate climate actions through e.g., the Science-Based Targets initiative (SBTi) (Maia and Garcia, 2022).

Natural resource depletion is of particular attention under the watch of global institutions' environmental initiatives (United Nations, 2015), such as The Circular Economy Action Plan and The European Green Deal (European Commission, 2015, 2019). The concept of circular economy (CE) has gained significant momentum within these initiatives and has taken a pivotal role in working to mitigate the depletion of resources in a manner that aligns with the Earth's ecological boundaries and supports economic growth (Andrews, 2015; Geissdoerfer *et al.*, 2017). CE implies the closing of material cycles and the preservation of resource value for as long as possible, intending to decouple economic growth from resource consumption (Kirchherr *et al.*, 2017). This logic is inherent to the frameworks such as Performance Economy or Functional Economy (Stahel, 2011).

When the research into product-service systems (PSS) commenced (Goedkoop *et al.*, 1999; Vandermerwe and Rada, 1988), the discourse was primarily related to the potential environmental benefits of PSS (Mont, 2004a). However, the research has since dispersed into many knowledge fields (Boehm and Thomas, 2013), and the focus has grown largely business-oriented, coinciding with the ascent of the servitisation movement (Baines *et al.*, 2009; Frederiksen *et al.*, 2021). In the 2000s, the prospect of "moving up the value chain" gained traction among manufacturers, and they increasingly sought to point their focus toward high-value and knowledge-intensive offerings (Baines *et al.*, 2007; Wise and Baumgartner, 2000).

However, numerous challenges arose (Martinez *et al.*, 2010), and few manufacturing companies succeeded with their service strategies (Ulaga and Reinartz, 2011), typically running into a service paradox, where they extended their service offering portfolios and incurred higher costs but have not materialised correspondingly higher returns, thus leading to a trough of disillusionment period in the PSS field (Gebauer *et al.*, 2005; Kuijken *et al.*, 2017).

PSS can be defined as compound through-life offerings consisting of tangible products and intangible services supported by necessary infrastructure and actor-networks, designed to provide more sustainable value (Kristensen and Remmen, 2019) than traditional product-only offerings (Mont, 2004b; Sarancic, Pigosso, Pezzotta, *et al.*, 2023). Numerous other definitions can be found in the literature, thus, on one hand, enriching perspectives on PSS and on the other hand reinforcing discord in the PSS design field (Haase *et al.*, 2017). In addition to abundant definitions, the body of knowledge is imbued with related or synonymous terms to PSS, namely functional (total care) products (Alonso-Rasgado *et al.*, 2004), integrated product services (Raja *et al.*, 2013), hybrid offerings (Ulaga and

Reinartz, 2011), service engineering (Sakao and Shimomura, 2007), technical product-service systems (Aurich *et al.*, 2006), servitisation (Baines *et al.*, 2009), industrial product-service systems (IPS2) (Meier *et al.*, 2010), solution-oriented partnerships (Manzini *et al.*, 2004), service science (Spohrer and Maglio, 2008), functional sales (Sundin *et al.*, 2005), value bundles (Becker *et al.*, 2012), and product-as-a-service (Kanazawa *et al.*, 2022). The common denominator of all these terms is the underlying paradigm shift from the disjointed consideration of products and services to a new understanding where integrated product and service design can act synergetically or super-additively to increase sustainable competitiveness (Kristensen and Remmen, 2019; Meier *et al.*, 2010).

Similarly, there are various PSS classifications in the literature based on different ways a PSS can: reduce environmental impact (Roy, 2000); enhance value creation (Manzini and Vezzoli, 2003); be designed (Tan *et al.*, 2010); have different levels of service content in the offering (Tukker, 2004; Tukker and Tischner, 2006). Tukker's (2004) typology is the most well-renowned in contemporary PSS literature (Beuren, Ferreira, *et al.*, 2013; Tukker, 2015) and it implies a spectrum of three different categories of offerings, namely product-, use-, and result-oriented, that can be further divided into eight types. The eight types can be distinguished as seen in the PSS decision tree (Figure 1) by product ownership party (customer or provider), function fulfilment party (provider or user), time frame (short, medium, or long) and exclusivity of product access, and value delivery type (activity-, count-, or result-based).

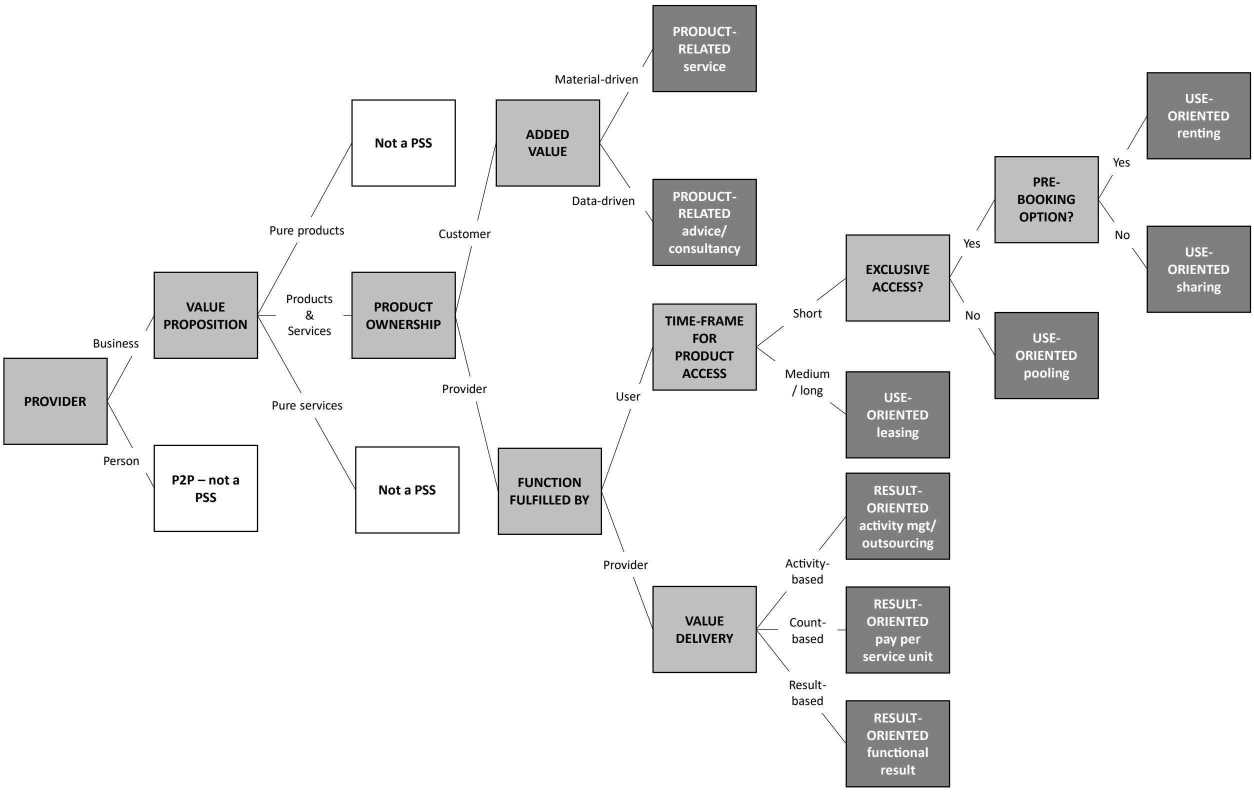

Figure 1. PSS decision tree showcasing the different PSS types (Pigosso and McAloone, 2022).

In light of the recent CE developments, as well as digitalisation advancements, PSS has again moved back into focus after a period of decreased attention, as one of the circular strategies with a promise of strongly contributing to sustainability (Hallstedt *et al.*, 2020; Pirola *et al.*, 2020). The positive contribution of PSS to sustainability is increasingly observed through a triple-bottom-line (TBL) perspective (Purvis *et al.*, 2019), although real economic, environmental, and social impacts are often subjects of debates in recent state-of-the-art literature (de Jesus Pacheco *et al.*, 2022; Roman *et al.*, 2023). As such, manufacturing companies nowadays have many motives to investigate the introduction of PSS offerings.

Economically, PSS can be rationalised as a means to create novel and more stable recurring revenue streams, secure customer lock-in, and gain a deeper understanding of customers' requirements (Arani *et al.*, 2023; Neely, 2008). These outcomes have the potential to drive up market valuations for companies in all industries (Kanazawa et al., 2022). From business and marketing viewpoints, PSS purports a shift from goods- to service-dominant logic, where value is no longer considered embedded in a physical artefact, rather the focus is shifted towards value in use (Grönroos and Voima, 2013; Kowalkowski, 2010; Vargo and Lusch, 2008).

Environmentally, service-oriented business models can prolong products' life, enhance resource and energy efficiency, thereby optimising their use phase, as well as reducing waste in production (Lindahl *et al.*, 2014; Pollard *et al.*, 2023). In addition to improving products' middle of life by narrowing and slowing the resource loops (Bocken *et al.*, 2016), PSS are known for potentially enabling several end-of-use strategies such as refurbishment, remanufacturing or repurposing to close the resource loop (Rittershaus *et al.*, 2023; Tukker, 2015).

Socially, PSS can positively impact customer acceptance, retention, and stronger relationships through multiple touchpoints and trust building (Chiu *et al.*, 2018). PSS supports the accumulation and security of knowledge-intensive jobs, as well as more justly balanced global work distribution (Aurich *et al.*, 2006). Furthermore, a number of basic human issues including human health, safety, equity, labour care, and education for socio-economic development can be reinforced through PSS (Chen, 2018).

Despite all these potential benefits and being seen as a key solution for achieving circularity (Fernandes *et al.*, 2020; Koide *et al.*, 2022), greater circularity or sustainability in any of the three dimensions are not guaranteed (Bech *et al.*, 2019; Kjaer *et al.*, 2018). The TBL impacts of PSS must be deliberately contemplated in the design of PSS, starting from the most impactful early design stages, to yield desirable results (Pigosso and McAloone, 2015; Rondini *et al.*, 2020; Sousa-Zomer and Miguel, 2017).

This thesis aims to introduce a systematic process that deliberately guides the early-stage PSS design towards greater sustainability potential both in academia and industry, where the context of the latter is elaborated in Section 1.2. Thereby, bridging the gaps elaborated in Section 1.3 and reaching the objective outlined in Section 1.4.

1.2 Empirical context and motivation

Although the state-of-the-art theoretical contributions outlined above represent the backbone of this research which pursues the creation of knowledge for generalisable applications, this research was substantially impacted by the prevailing empirical circumstances upon which the PhD project was established.

The PhD project was supported by the Manufacturing Academy of Denmark (MADE) as a part of the research and innovation program MADE FAST (flexible, agile, sustainable, and talent-based). MADE is the Danish non-profit consortium for advanced manufacturing that brings together manufacturing companies, higher-education institutions, and Research and Technology Organisations (RTOs) with the overarching aim of elevating Danish manufacturing capabilities.

This research was conducted in close collaboration with the case company Aasted ApS, a MADE member. Aasted is a mid-sized worldwide market-leading manufacturer of production solutions within the chocolate, bakery, and confectionery industries, headquartered in Denmark. Aasted supplies capital goods, among others including complete processing lines, machinery, and equipment for moulding, extrusion, depositing, tempering, cooling, enrobing, and baking.

The underlying conditions of this research spurred a tremendous opportunity to identify research gaps and study contemporary challenges relevant to address at the intersection of pragmatic industrial needs and burning issues in the recent literature. Therefore, this research guided by a scientific methodology benefited from a quintessential balance of rigour and relevance.

During the period of this study, which was conducted from October 2020 to October 2023, the company under investigation was initiating PSS development as a way to support and operationalise the recently adopted TBL-oriented strategy. In that regard, the company could be considered representative of many companies, since TBL-oriented strategies are observed as the most common way to instil sustainability in a business (Palmer and Flanagan, 2016). Apart from having set ambitious emission reduction and service-business growth targets despite the limited previous experience with PSS, the company explicitly expressed the need for a systematic PSS design framework in line with the strategy.

In addition to the evident PSS opportunities tied to the steadily expanding installed product base, owing to the aggregation of past sales and longer product life cycles (Gebauer *et al.*, 2010; Oliva and Kallenberg, 2003), the company wished to expand further into PSS offerings with more saturated service content (use- and result-oriented PSS), such as selling product usage or performance rather than the product itself with subsequently appended services (Kuo *et al.*, 2019; Wise and Baumgartner, 2000).

The company's management understood the challenge of being an engineering-to-order (ETO) company focused on designing capital (investment) goods rather than services and recognised the need for a fundamental paradigm shift and reliance on expert knowledge for service offerings such as inspection and maintenance (Mourtzis *et al.*, 2017), which are the cornerstones of industrial (Meier *et al.*, 2010) i.e., technical PSS (Aurich *et al.*, 2006). The management was familiar with the notion of PSS but wanted to understand how to methodically design and evaluate different PSS concepts every time and built that knowledge into their existing product development process. Additionally, they were cognisant of the limited scope of service offerings in the capital goods sector, as reported by Adrodegari et al. (2018), and the historically modest financial returns of PSS, as noted by Neely (2008). Despite the adverse outlook, the company still chose to push forward with PSS development due to their commitment to sustainability, thereby steering the scope of research towards timely pertinence.

1.3 Research scope and gaps

This thesis is sharply concentrated on early-stage PSS design in capital goods manufacturing companies, such as the case company described above. The research has been scoped to primarily deal with capital goods manufacturing companies both due to the established empirical setting and the numerous gaps identified in theory and practice.

This delimitation points to a subset of PSS, often coined by synonymous terms of technical (t-PSS) and industrial (IPS^2) PSS (Mourtzis *et al.*, 2020), which emphasise PSS' manufacturing and technical aspects (Azarenko *et al.*, 2009). As the research findings within this subset enrich the overall body of knowledge on the broader concept of PSS, and the availability of knowledge on the broader concept of PSS is much more widespread and sought after, the term PSS is used throughout this thesis.

PSS design in capital goods manufacturing companies is characterised by several peculiarities, underscoring the investment nature of both goods and services, the relatively higher monetary value of the high-quality goods, and the business-to-business (B2B) relationship between the original equipment manufacturer OEM and their customers (Aurich *et al.*, 2006).

These peculiarities result in several differences in the approach to designing PSS when compared to manufacturers primarily operating in the business-to-consumer (B2C) space. Due to the high monetary value of capital goods, the companies often focus on tapping into the earning potential of the already existing base of installed products, intending to generate additional service revenue without excessive investments (Gebauer *et al.*, 2010). In the B2B setting, customers' influence on design decisions is much larger (Pekkarinen and Ulkuniemi, 2008), as just a few key accounts might drive a significant portion of the company's revenue. Those customers are likewise manufacturing companies, therefore, the OEM in most cases has no access to the final customer (Sarancic *et al.*, 2021a) to solicit complete feedback on their offerings. Further, the products have a lower release cadence due to their complexity in development and also in the customer adjustment period to the new offering which usually requires new processes, training, as well as prior industry knowledge. Even though the willingness to pay is higher in the B2B setting, the sales process is much different, because the target audience is a group of decision-makers within the customers' organisation whose focus is on functionality and return on investment (ROI) (Rėklaitis and Pilelienė, 2019). The difference is also observable in the lack of distinction between the service and the product during any stage of PSS' life cycle (Meier *et al.*, 2010) and because customer needs most often cannot be appropriately satisfied by "off the shelf" offerings but necessitate customised solutions (Aurich *et al.*, 2006), thereby inherently matching an ETO's *modus operandi*. Therefore, in such a setting, the complexity of the PSS design is considered higher than in a B2C relationship (Mourtzis *et al.*, 2020).

Despite the presence of PSS offerings in capital goods manufacturing companies for decades, such offerings are not as widespread, nor are the capital goods companies as mature for PSS design as previously expected (Adrodegari *et al.*, 2018; Brissaud *et al.*, 2022). PSS implementation in this setting is very challenging and context-dependent, hindering the maturation and generalisation of still very raw design methodologies which fail to capture all the intricacies of PSS design (Brissaud *et al.*, 2022).

Early-stage PSS design, culminating in an assessable PSS concept (Welp and Sadek, 2008) and entailing planning and conceptualisation stages (Rosa *et al.*, 2021), is of utmost importance for the performance and the success of PSS offerings (Peruzzini and Wiesner, 2020; Sassanelli *et al.*, 2016; Sousa-Zomer and Miguel, 2017). The criticality of the early stages of any creative innovation process is reflected in the decisions that contribute to the majority of both financial and environmental costs and benefits incurred throughout the life cycle (Chang *et al.*, 2019; Geum and Park, 2011; Roy and Cheruvu, 2009).

Irrespective of the realisation of the significance of early-stage PSS design on a global scale, with the service sector estimated at 70-80 % of GDP in most developed countries (Moser *et al.*, 2015), manufacturing companies still face major challenges while introducing PSS due to several other reasons (Kolling *et al.*, 2022). These reasons are considered to manifest due to four knowledge gaps in academia and industry, which this PhD thesis both identifies and strives to address.

Gap A. The dispersion of the multi-disciplinary PSS research field and the multitude of motivating and prohibiting factors to introduce PSS offerings.

PSS design requires multi-disciplinary and holistic approaches (Gräßler and Pottebaum, 2021), however, the research field is permeated with numerous partial and niche approaches, especially within the engineering design, business management, and information systems sub-tracks of the PSS research domain (Boehm and Thomas, 2013). A multitude of existing design approaches (Qu *et al.*, 2016) coupled with the entanglement stemming from the heterogeneity of design elements and variants to be simultaneously considered magnify the complexity even further (Barravecchia *et al.*, 2020).

There is insufficient interconnectivity between the disparate PSS research fields, and it is considered that their integration and consolidation in the years ahead is essential to provide a complete perspective on the PSS phenomenon (Annarelli *et al.*, 2016; McAloone and Pigosso, 2017).

The introduction of PSS offerings by manufacturing companies can be motivated by numerous drivers across the TBL spectrum, as described in the sections above, thereby setting the direction for PSS design, but the business imperative is most often the dominant factor (Vasantha *et al.*, 2012). As additional business drivers, manufacturing companies observe PSS as a good strategy to face a competitive business environment and differentiate themselves, expand to new markets, gain access to installed product base, establish aftermarket and in-use data control, anticipate upcoming legislation, diversify and flexibilise offerings portfolio (inherently important for ETOs), improve customer service, and increase overall equipment effectiveness (OEE) (Sarancic *et al.*, 2021b, 2021a).

Prohibiting factors to introduce PSS are many, in technical, economic, organisational, and societal domains (Mont, 2004a; Sarancic *et al.*, 2021b, 2021a). On the technical front, integrating diverse products and services into a coherent system can be complex, requiring interoperability and advanced technologies. Economically, transitioning from a traditional product-centric model to a PSS often involves substantial initial investments and necessitates new pricing models. Organizational barriers include resistance to change within established industries and firms, as well as the need for new skills and competencies. Lastly, societal acceptance and regulatory frameworks may lag behind the innovative nature of PSS, posing challenges in terms of market acceptance and legal compliance

The prioritisation of these motives and hurdles or their combination to address is considered to have a significant impact on the PSS design process and the final offering delivered to the market, which is something that a unified framework should be able to accommodate.

Gap B. Lack of comprehensive and generic structured approaches to the early-stage PSS design.

PSS design is accompanied by unique challenges when compared to product and service design, respectively, where the complexity has largely been harnessed and the design processes well-incorporated (Olsson and Edvardsson, 1996; Ulrich et al., 2020). In comparison to those two adjacent fields, a greater variety of expertise is needed for successful PSS design (Nemoto *et al.*, 2015). The lack of such intertwined expertise in literature and practice usually leads to principally intuitive and ad hoc early-stage design processes (Gokula Vijaykumar *et al.*, 2013), with many uncertain iterations due to the obscurity of the process, available data, and requirements (Rondini *et al.*, 2020; Wallin *et al.*, 2015). The specificity of the early-stage PSS design, in contrast to product and service design, manifests in the much broader object of design that additionally includes the business model, the actor-network, and supporting infrastructure, thereby blurring the distinction between offering design and the manufacturing company's development as a whole (Maussang *et al.*, 2009; Sarancic, Pigosso and McAloone, 2023; Sarancic, Pigosso, Pezzotta, *et al.*, 2023).

The importance and the need for integrated generic structured design support for early-stage PSS design are widely recognised, but the support is absent in the literature (Bertoni *et al.*, 2019; Brissaud *et al.*, 2022; Guillon *et al.*, 2021). Although many PSS design methodologies have been proposed in the literature, most lack a complete step-by-step sequence of the PSS design process, limiting their usefulness to PSS designers (Chiu *et al.*, 2018; Moro *et al.*, 2023; Tran and Park, 2014). The existing process models are often deficient and inefficient, leading to a flawed early-stage design process that primarily relies on designers' experience and abilities rather than systematic techniques (Kim and Yoon, 2012; Sakao and Neramballi, 2020).

Early-stage design of PSS presents a unique opportunity to use systematic approaches to avoid sub-optimal decisions and make the least expensive changes (Bertoni *et al.*, 2019; Schmidt *et al.*, 2015). This can be achieved by capitalising on the positive effects and avoiding the negative effects of PSS through the use of predefined generic PSS design process models (Vasantha *et al.*, 2015). Therefore, a more structured and complete generic approach to PSS design for manufacturers is much needed to improve the efficiency and effectiveness of the design process (Haber and Fargnoli, 2017a; Vezzoli *et al.*, 2015).

Gap C. Lack of industrially implementable PSS design approaches and guidelines to support their adoption by manufacturing companies.

The implementation of PSS design approaches in the industrial context is challenging due to various reasons (Andriankaja *et al.*, 2016). One of the significant issues is the lack of guidelines and limited understanding of how industrial companies implement and manage PSS (Cavalieri *et al.*, 2020). Another challenge relates to the companies' internal inability to organise themselves appropriately for the design and implementation (Pezzotta *et al.*, 2018). Moreover, the vague border between PSS designers and managers further complicates the process by camouflaging the distribution of responsibilities (Sarancic, Pigosso and McAloone, 2023).

There is a lack of processes to effectively support the industrial implementation of PSS design approaches in the literature (Moro *et al.*, 2022; Sakao and Neramballi, 2020). The existing PSS design approaches are often difficult to implement, resulting in a limited adoption rate and the reluctance of industry to embrace new PSS design approaches (Baines *et al.*, 2007; Matschewsky *et al.*, 2015; Sassanelli *et al.*, 2019). The low usability of existing approaches mirrors the well-known mismatch in the abstraction level between methods developed in academia versus industry (Beuren, Gomes Ferreira, *et al.*, 2013), implying the need to instantiate the generic approaches to specific contexts where they meet specific stakeholders' requirements while retaining the elements crucial for comprehension and utility (Polyvyanyy *et al.*, 2015).

This need to facilitate early-stage PSS design through systematic approaches that can be tailored to individual practitioner contexts has been long vocalised in the literature (Becker et al., 2010; Yang and Xing, 2013a), and it is considered that explicit instantiation guidelines can ease the PSS design approach implementation in manufacturing companies.

Gap D. Lack of sustainability considerations and structured ex-ante sustainability evaluation approaches for early-stage PSS design.

Sustainability in early-stage PSS design is tackled sporadically and superficially in the extant literature (Moro *et al.*, 2022; Qu *et al.*, 2016). Numerous contributions draw attention to the lack of established methods to holistically assess PSS concepts from the TBL perspective and call for systematic guiding principles to do so (López *et al.*, 2020; Rondini *et al.*, 2020; Song and Sakao, 2017).

Researchers were historically more engaged in PSS design than evaluation (Qu *et al.*, 2016), but even in the design process, sustainability was rarely explicitly addressed (Kristensen and Remmen, 2019) despite the consensus on the importance of considering it in the design process (Pigosso *et al.*, 2013).

In the existing PSS sustainability assessment methods, the focus is put on ex-post, rather than ex-ante approaches which could have greater significance (Kjaer *et al.*, 2018). The ex-ante consideration is crucial as a company's initial sustainability awareness is monumental for the contribution of PSS to sustainability (Kühl et al., 2022). PSS early-stage evaluation is by nature a soft task necessitating human activities, but it can increase the likelihood of conceiving more sustainable PSS offerings (Kim *et al.*, 2016). However, existing methods hinder early-stage PSS assessment in its critical aspects of sustainability requirements definition (Chen *et al.*, 2019), concurrent consideration of economic, environmental and social performance (Annarelli *et al.*, 2016), the inclusion of the aspect of sustainable PSS value (Hart *et al.*, 2003; Rondini *et al.*, 2020), and taking into account the life cycle thinking (Meier *et al.*, 2010; Yang *et al.*, 2014). Thus, prohibiting the connection of business performance to sustainable development (Chou *et al.*, 2015), which could be established through comprehensive PSS concept screening.

Overall, PSS sustainability assessment is a critical question that needs to be carefully addressed by designers starting from the early design stages and by considering the intrinsic complexity of sustainability (Doualle *et al.*, 2016, 2020; Tran and Park, 2016)

The four gaps (A, B, C, and D) described above are depicted in Figure 2 as problems to address to obtain the four principal results (Drivers & barriers, Generic process model, Instantiation guidelines, and Sustainability screening tool) in order to devise a comprehensive framework. The four gaps can be unified to succinctly describe the **major research gap**:

The lack of a usable and comprehensive generic framework that can support early-stage PSS design for sustainability in capital goods manufacturing companies.

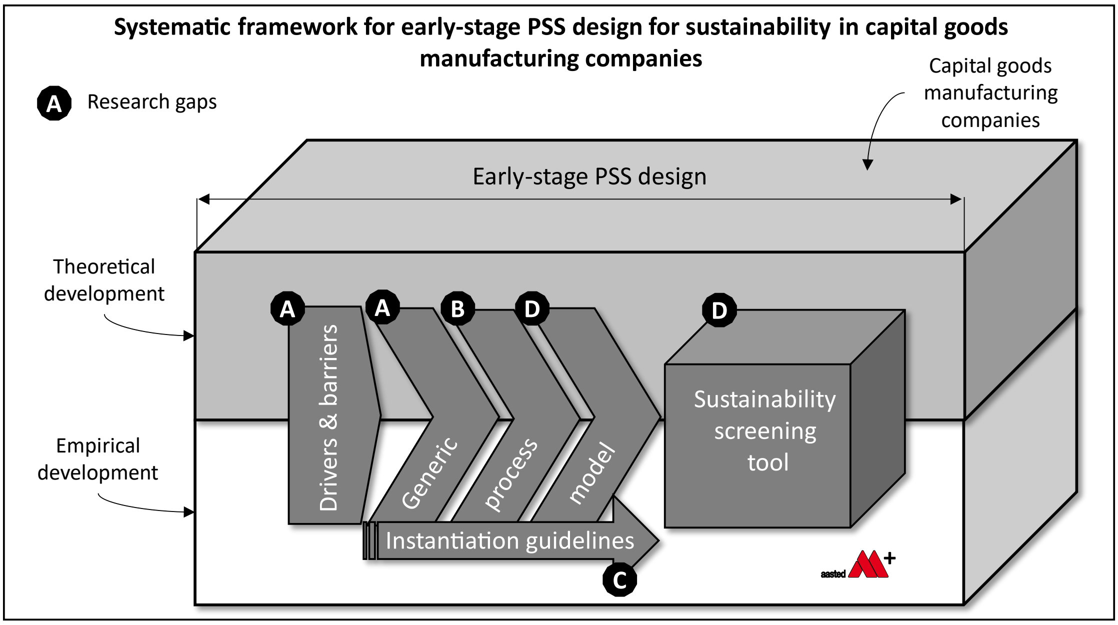

Figure 2. Research gaps and scope in the context of the framework developed in this PhD project.

1.4 Objective and hypothesis

This PhD thesis aims to support capital goods manufacturing companies in early-stage PSS design for sustainability and thereby contribute to the decoupling of value creation and economic growth from resource consumption. To support them, the overarching objective of this research is to:

Develop a systematised framework to support managers in early-stage PSS design for sustainability in capital goods manufacturing companies.

More specifically, the systematised framework (visualised in Figure 2) intends to provide support to managers in capital goods manufacturing companies to: (i) scope and understand the drivers and barriers to introducing PSS offerings, (ii) systematically guide the early-stage PSS design process, (iii) successfully tailor and embed the design process in the company, (iv) comprehensively screen PSS concepts to determine their adherence to the TBL-oriented corporate strategy.

Grounded in this objective, the overall hypothesis investigated in this thesis is formulated as follows:

The systematisation of a framework for early-stage PSS design for sustainability can provide useful and usable support for the design of PSS concepts in capital goods manufacturing companies aligned with a TBL-oriented strategy.

Where the *usefulness* and *usability* of the support refer to the ability of the support to serve its practical purpose in yielding expected outputs (validation), and the ease of support usage by the manufacturing companies (evaluation), respectively.

A *PSS concept* is defined as an actionable and assessable design proposal describing the total PSS solution including the system's composition, its functionalities, and business model that fulfil the requirements of the involved actor-network (Sarancic *et al.*, 2022).

TBL-oriented strategy is any corporate strategy focused on comprehensively improving a company’s bottom line from economic, environmental, and social perspectives.

1.5 Research questions

This thesis focuses on four research questions (RQs), which are formulated based on the research gaps, the overarching objective, and the overall hypothesis explained above. The RQs are further branched into sub-questions to structure and guide the research activities. The questions and sub-questions are:

RQ1*: What are the drivers and barriers for manufacturing companies to introduce PSS offerings?*

RQ1.1: What are the real-world perceived drivers and barriers for PSS introduction in a capital good manufacturing company and how do they compare to literature findings?

Although the research in this thesis commenced by studying PSS design in manufacturing companies in general, the initial studies narrowed down the scope to focus on capital goods manufacturing companies, as elaborated in Sections 1.3 and 3.1.

RQ2: *How to systematise the existing perspectives on early-stage PSS design in literature to develop a generic process model (GPM) for capital goods manufacturing companies?*

RQ2.1: What are the existing approaches for early-stage PSS design in the literature?

RQ2.2: What are the main phases, activities, tools, and constituent entities in the existing approaches to early-stage PSS design?

RQ2.3: What are the sustainability considerations in the existing early-stage PSS design approaches and how to incorporate them into the GPM?

RQ2.4: What is the usefulness and usability of the GPM within capital goods manufacturing companies?

A generic process model comprises a comprehensive collection of organised practices and supporting elements that provide guidance for the appropriate execution of the design process and can effectively handle its intricacies (Pieroni *et al.*, 2019a; Smirnov *et al.*, 2012).

Constituent entities refer to the objects or concepts that are the focus of design or analysis, and which can be categorised into a cohesive cluster, *activities* refer to the essential actions that must be taken during the design process, while *tools* are design supports that can assist in achieving the most effective outcomes during the design process (Sarancic, Pigosso, Pezzotta, *et al.*, 2023).

RQ3: *How to enable the application of the GPM in practice to support PSS design in capital goods manufacturing companies?*

RQ3.1: What are the actions the capital goods manufacturing companies took to instantiate the GPM to their specific contexts?

RQ3.2: What are the challenges the capital goods manufacturing companies encounter during the GPM instantiation?

Instantiation implies the abstraction of a generic process in order to reduce its complexity, facilitate analysis and communication, and identify significant elements of the model within a specific context, with the aim of meeting stakeholders' requirements while retaining essential information (Polyvyanyy *et al.*, 2015).

RQ4: *How to systematise the existing perspectives on PSS concept sustainability to develop a sustainability screening tool for PSS concepts?*

RQ4.1: What are the existing approaches for PSS concept sustainability evaluation?

RQ4.2: What are the key dimensions to consider in ex-ante PSS concept sustainability screening?

RQ4.3: How to identify TBL benefit and cost hotspots of a PSS concept?

RQ4.4: What is the usefulness and usability of the sustainability screening tool for PSS concepts within capital goods manufacturing companies?

Ex-ante PSS concept screening is a simplified assessment of alternative PSS concepts aimed at enhancing the prospect of successful early-stage PSS design for sustainability particularly well-suited for the early stages of PSS design where limited data and context comprehension are available (Sarancic *et al.*, 2022).

2 Research Methodology

The second chapter presents the research methodology utilised as the mainframe of this PhD thesis, which guided tackling the research questions and obtaining the key results (section 2.1). Further, the chapter elaborates on the research methods practised during the research (section 2.2).

2.1 Design Research Methodology

Design Research Methodology (DRM) (Blessing and Chakrabarti, 2009) (Figure 3) was used to structure this PhD thesis. The DRM is a rigorous scientific framework that includes a set of supporting methods and guidelines to conduct design research more efficiently and effectively. The purpose of design research is the development of understanding and knowledge about design, and the development of support for design (Blessing and Chakrabarti, 2009). DRM capacitates a thorough inquiry and introduces rigour into the identification of relevant a challenge to address, understanding it, developing a solution to the challenge, and finally, evaluating the success of the solution.

The methodology consists of four stages: Research Clarification (RC), Descriptive Study I (DS-I), Prescriptive Study (PS), and Descriptive Study II (DS-II), which are explained in sub-sections 2.1.1-2.1.4. Despite its stages, DRM is not to be regarded as rigid and linear, but rather an adaptable framework, where its stages can be executed concurrently and iteratively. This characteristic makes DRM particularly suitable for the industrially applied kind of research exercised in this PhD thesis, which can be conducted through multiple cycles of DRM. The adaptability of DRM to a wide variety of industrial settings, research methods, and empirical sources of data makes it highly suitable for the context of this research (Blessing and Chakrabarti, 2009), which is distinctly entangled with pragmatic application in capital goods manufacturing companies.

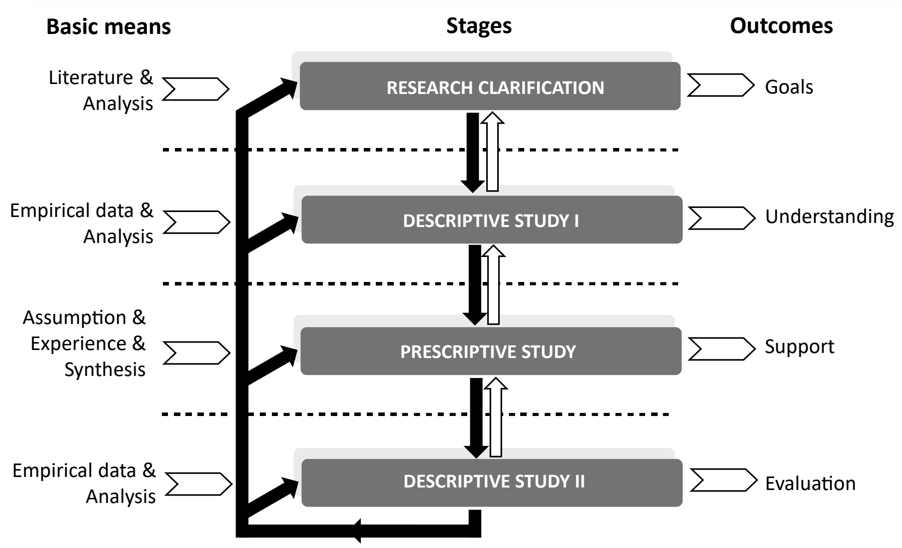

Figure 3. DRM, adopted from Blessing and Chakrabarti (2009).

The DRM has been broadly adopted by extant PSS design research (see e.g., Bertoni, 2019; Mitake et al., 2020; Shimomura et al., 2018; Tan et al., 2010). The historical efficacy of this methodology in the PSS design research demonstrates its aptness, and thereby it has been chosen as the mainframe for this study over other similar methodologies such as the Design Science Research Methodology (DSRM) (Hevner *et al.*, 2010).

2.1.1 Research clarification

The RC stage is critical to defining realistic and worthwhile research goals that can be achieved within the available project timeframe. During this stage, an understanding of the current situation and desired outcomes of the project, as well as the project plan and structure are outlined. This includes exploring and clarifying initial evidence or indications to support assumptions regarding the existing situation and research problem, mainly through exploratory literature review and analysis (Blessing and Chakrabarti, 2009). This initial review and analysis aim to identify relevant research gaps, as a basis of insights to formulate a set of initial RQs that would evolve throughout the project and crystalise the research scope, objective and hypothesis (Chapter 1).

The exploratory literature review and analysis in this PhD project focused primarily on the drivers and barriers for manufacturing companies to introduce PSS, in both theoretical (Sarancic *et al.*, 2021a) and empirical landscapes (Sarancic *et al.*, 2021b), thus also informing the answers to RQ1 and RQ1.1. The review was further expanded to initially explore PSS design approaches and the relationship between PSS, CE, and TBL sustainability. One of the principal outcomes of the RC was the delimitation of further study on capital goods manufacturing companies.

The RC was concluded with the definition of the PhD project plan, with a decision to structure it into three subsequent cycles of the DRM methodology, C1, C2, and C3, with the appropriate depth of corresponding DS-I, PS, and DS-II studies in each cycle.

2.1.2 Descriptive study I

The primary aim of DS-I is to provide a detailed account of the existing situation, to gain a better understanding of the phenomena and to highlight potential problems. This stage is also used to demonstrate the relevance of the research topic and to clarify and illustrate the main arguments. Moreover, it is used to identify the factors that are most pertinent to address in order to improve the existing situation.

The main outcome of a DS-I stage is a comprehensive portrayal of the phenomena being investigated, along with an analysis of the factors that influence it. The insights gathered from this stage are essential for the development of the design support and for evaluating its effectiveness in the later stages of DRM. In this PhD thesis, the DS-I stage was both theoretically and empirically driven. The theoretical DS-I relied on review-based, exploratory, and qualitative approaches, while the empirical DS-I relied on interviews, case studies, and surveys (Blessing and Chakrabarti, 2009; Robson and McCartan, 2016).

This PhD thesis consists of three DS-I studies, one in each of the three cycles of DRM, which were useful in primarily answering RQ2.1.-2.3., RQ3.1-3.2, and RQ4.1.-4.2., respectively, thus contributing to answering the main research questions.

2.1.3 Prescriptive study

The PS stage aims to address research and practical problems by developing and initially evaluating design support that suggests how design tasks should be carried out to improve the existing situation. PS uses the understanding obtained from DS-I to determine the most suitable factors to be addressed. The development of the support involves creativity and imagination, which can be prompted by problem-solving and empirical development methods. The support can include any means, aids, or measures that improve design, such as methodologies, procedures, techniques, software tools, guidelines, knowledge bases, or checklists (Blessing and Chakrabarti, 2009). The deliverables of PS are the actual support, support documentation, initial evaluation of the support with respect to its functionality and consistency, and an outline of the detailed evaluation plan to be used in DS-II.

This PhD thesis involves three comprehensive prescriptive studies in the three DRM cycles (C1, C2, and C3), which incorporate conceptualisation, documentation, realisation, and initial evaluation of various types of support. The three PS studies covered:

- C1: development of a systematic GPM for early-stage sustainable PSS design in capital goods manufacturing companies. This deliverable primarily tackles RQ2 and RQ2.3.
- C2: development of comprehensive GPM instantiation guidelines for capital goods manufacturing companies. This deliverable primarily tackles RQ3.

- C3: development of the TBL sustainability screening tool (BESST) for PSS concepts. This deliverable primarily tackles RQ4 and RQ4.3.

2.1.4 Descriptive study II

The DS-II serves the purpose of assessing the support developed in the PS stage and ensuring its successful implementation in practice. It is similar to DS-I in that it aims to create an understanding, but it differs in that it seeks to comprehend the impact of the developed support and its ability to realise the desired situation (Blessing and Chakrabarti, 2009). Therefore, the main objectives of DS-II include determining whether the support can be effectively used for the intended task and whether it has the expected impact on key factors. Additionally, DS-II aims to identify the necessary improvements for both the support and the criteria used to evaluate it.

The DS-II stage provides insight into the usefulness and usability of the support, referring to its ability to serve its practical purpose in producing expected outputs, and the ease of its usage by capital goods manufacturing companies, respectively. Empirical studies are often conducted during this stage to gain an understanding of how the support performs in a real setting where the phenomenon occurs.

Two DS-II studies have been used in C1 and C3 of DRM in this PhD thesis in order to evaluate the respective results of the PS in C1 and C3 (Sub-section 2.1.3). The two DS-II studies covered mainly RQ2.4. (C1) and RQ4.4. (C3). A formal DS-II study has not been used in C2 of this thesis to evaluate the support developed in PS, as the evaluation of the GPM instantiation guidelines occurred concurrently with their development in the empirical setting.

2.1.5 The use of DRM in this PhD thesis

A detailed visualisation of the use of DRM and its stages in this PhD thesis can be seen in Figure 4. The upper part of the Figure shows the RQs, DRM stages, research methods, results, and publications in this thesis. The lower part of the Figure (below the arrow) shows the publications mapped once again on the same illustration used to indicate the research gaps in Figure 2, for enhanced clarity. Finally, the legend of the symbols used in the Figure is elaborated on the righthand margin of the Figure 4.

In practical research such as that presented in this thesis, the pre-conceived methodology may not always align with the ever-changing reality of business environments. To overcome this challenge, the flexibility of DRM was used to execute research iteratively in three cycles (C1, C2, and C3) which do not necessarily represent a chronological course of actions. For instance, the third cycle was chronologically executed before the others, but in the systematic framework depicted in the lower part of Figure 4, the results of the third cycle (screening tool) should be used by the companies at the end of the early-stage design. Moreover, prescriptive and descriptive studies were conducted concurrently across various companies, progressively co-developing and refining the support, as in the second cycle of this research.

In adherence to the transdisciplinary approach and pragmatic orientation of this study, a blend of research methods was utilised to facilitate the resolution of RQs in three cycles of DRM. Each of the practised research methods is explained in Section 2.2.

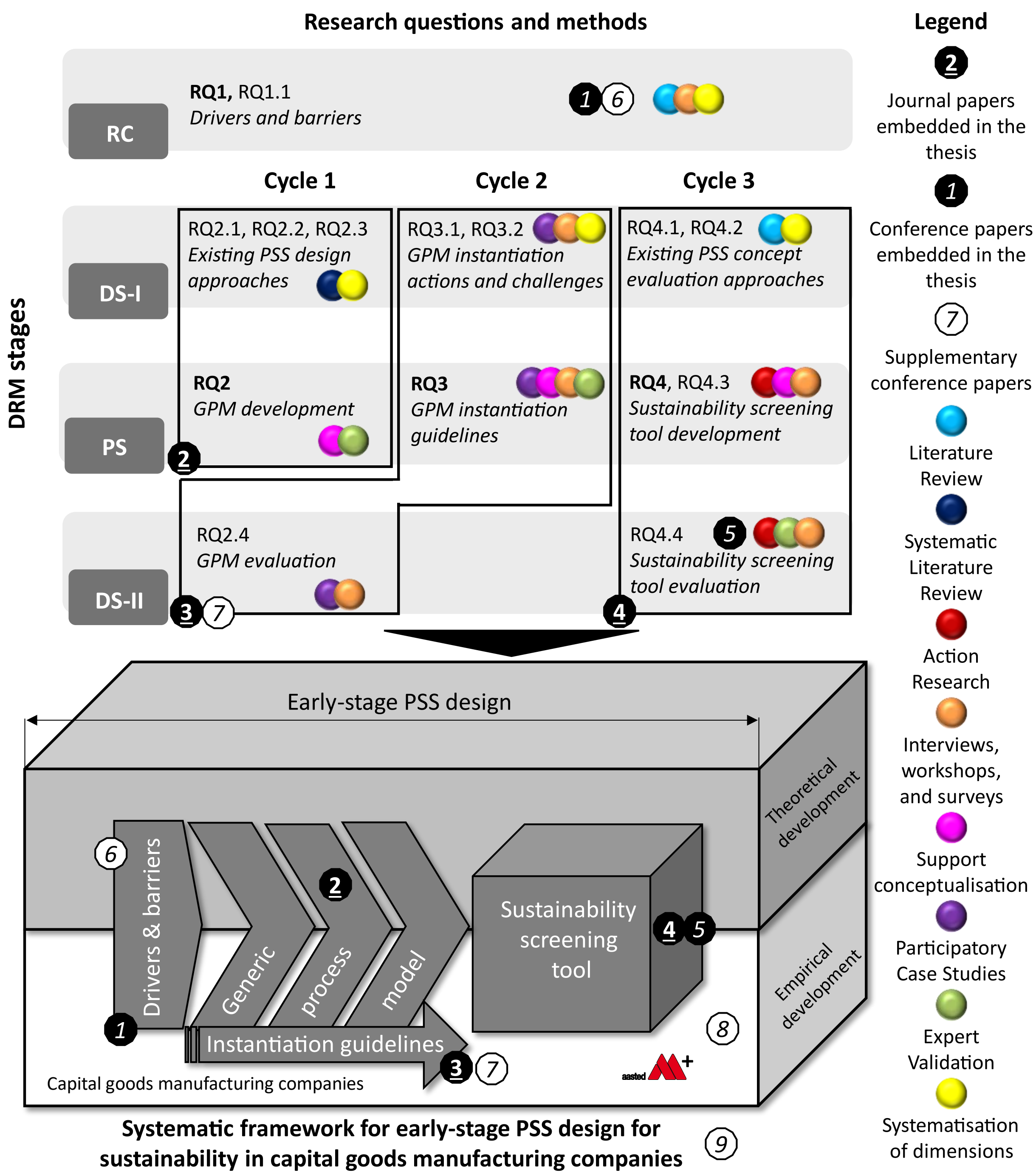

Figure 4. The RQs, DRM stages, research methods, results, and publications of this thesis.

2.2 Research methods

In this section, all the research methods applied throughout the three cycles of DRM, as illustrated in Figure 4, are described. The research methods include literature reviews (Section 2.2.1), action research (AR) (Section 2.2.2), interviews, workshops, and surveys (Section 2.2.3), systematisation of dimensions (Section 2.2.4), conceptualisation of the supports (Section 2.2.5), expert validation (Section 2.2.6), and participatory case studies (Section 2.2.7).

2.2.1 Literature reviews and systematic literature reviews

A literature review is a critical evaluation and synthesis of existing scholarly articles on a specific topic or research question that aims to provide an overview and analysis of the current state of knowledge in a particular area of study. A systematic literature review (SLR) is a more rigorous and structured approach to literature review (Munn *et al.*, 2018). The SLR protocol used in this thesis follows the steps of planning, execution, and result analysis, as proposed by (de Almeida Biolchini *et al.*, 2007).

SLR can significantly enhance the validity of assertions within a specific research domain by improving the reliability of approaches for developing novel methodologies and tools. Through creating generalisations, illuminating new aspects and issues, and guiding future research, SLR represents an integrative research approach that goes beyond a mere reorganisation of previously known and published knowledge (de Almeida Biolchini *et al.*, 2007).

Literature reviews were in this research used as a part of RC to identify drivers and barriers, as well as to scope the research, and in the third cycle DS-I study to identify the existing PSS sustainability screening approaches. SLR was applied in the DS-I study in the first cycle of DRM to uncover the existing PSS design approaches and all their intricacies.

2.2.2 Action research

Action research (AR) is a research methodology that represents research in action, rather than research about action (Coughlan and Coghlan, 2002). It involves systematic and reflective inquiry by participating practitioners concurrently with the action being executed, hence, making it particularly suitable in the empirical setting upon which this research project was established.

AR is a cyclical process that involves planning, action, observation, and reflection, with each cycle leading to new insights and improvements (Mathiassen, 2017). AR matches extraordinarily well with the DRM framework because of their complementary cyclical processes involving the PS and DS-II stages (Blessing and Chakrabarti, 2009). As such, it has been successfully used both for PSS-related research (Linder and Williander, 2017; Tonelli *et al.*, 2009) and in combination with DRM (Blessing and Chakrabarti, 2009; Pieroni, 2020).

The central tenets of this emancipatory method are improvement and involvement; thus, AR can be used for the betterment and evaluation of practices, understanding, or solutions within a specific context (Robson and McCartan, 2016). AR is suitable for simultaneous use with other research methods, therefore making it highly applicable in the third cycle of DRM in this research for both the screening tool development and evaluation (PS and DS-II, respectively).

2.2.3 Interviews, workshops, and surveys

In this PhD thesis, diverse methods were used for data collection and as means of receiving evaluative feedback regarding the developed supports from the involved case companies.

Primarily semi-structured exploratory interviews (Dyer and Wilkins, 1991) were utilised in this research. Semi-structured interviews imply a predetermined set of topics to be covered in the interview. However, there is significant flexibility in terms of the question order, the phrasing of those questions, and the amount of emphasis placed on each topic. This approach is most effective when the interviewer is closely involved in the research process (Robson and McCartan, 2016), as is the case in AR. The interviews were in this research used throughout the DRM. In RC, perceived drivers and barriers to PSS design were elicited from the main case company representatives. In the first cycle, a partial evaluation of the GPM in DS-II was obtained through feedback from the case companies in the form of interviews. In the second cycle, interviews were used to elicit the actions and challenges to GPM instantiation (DS-I) and to initially evaluate the instantiation guidelines (PS). In the third cycle, the interviews were used to elicit the main case company's requirements for the screening tool and evaluate it (PS and DS-II).

Workshops are a commonly used scientific method for collaboration and knowledge sharing among researchers and industrial practitioners (Blessing and Chakrabarti, 2009). Workshops are structured events that bring together a group of individuals with expertise in a particular field to share their experiences, knowledge, and ideas on a specific topic. Workshops facilitate the identification and exploration of relevant factors in a given domain by enabling the comprehension of complex work and knowledge processes, ultimately aiding researchers in uncovering previously unknown factors (Ørngreen and Levinsen, 2017). In this research, workshops were primarily used as a way of introducing the developed supports to the companies with the aim of receiving feedback, as well as for the instantiation of the GPM (PS studies in cycles 2 and 3).

Survey deployment is a common research method that involves data collection from a sample of individuals using standardised questionnaires (Robson and McCartan, 2016). The results are then analysed to understand the opinions of the population. In this research, surveys were used mostly for assessment purposes after the workshops where the developed supports were rolled out (DS-II studies in cycles 1 and 3).

2.2.4 Systematisation of dimensions

The systematisation of the vast knowledge bases was conducted several times within this research, primarily followed by the data collection either through literature reviews or interviews. The systematisation involved content analysis, coding, thematic organisation, and identification of emergent patterns (Dresch *et al.*, 2015; Yin, 2003). Such methods were in this research used to systematise drivers and barriers in RC, and all the findings in the DS-I stages of all three DRM cycles. Namely, dimensions related to the existing PSS design approaches in C1, actions and challenges to GPM instantiation in C2 and the dimensions related to the existing PSS concept screening approaches in C3.

2.2.5 Conceptualisation of the supports

The conceptualisation of the three main supports (GPM, instantiation guidelines, and the screening tool) conceived in the three PS studies followed the DRM recommendations, which firstly rely on usability and usefulness requirement definition (Blessing and Chakrabarti, 2009). The three supports were then built using creativity and imagination based on the beforehand systematised knowledge in DS-I studies, where patterns and individual hypotheses to be tested in consecutive papers were identified. These patterns and hypotheses were systematically tested and refined through experimentation and analysis of the emerging design support.

2.2.6 Expert validation

Evaluation by academic specialists can improve the research by generating suggestions and opinions about it, which can then be addressed by making modifications to the developed support, with a focus on boosting it with respect to e.g., consistency, completeness, or clarity (Pieroni, 2020; Pigosso *et al.*, 2013).

The expert validation was applied in the first cycle DS-II study to validate the paper-based prototype of the GPM. It was further used in the DS-II study in C3 through workshops to evaluate the proposed sustainability screening tool.

2.2.7 Participatory case studies

A participatory case study is a research method that involves collaboration between researchers and the subjects of the study in the design and implementation of the research (Reilly, 2010).

While both participatory case studies and AR involve collaboration and engagement with study participants (Coughlan and Coghlan, 2002), the key difference is their motivation, commitment, and approach (Baskerville, 1997). A participatory case study is focused on gaining insights into complex organisational issues such as the new process implementation (e.g., GPM instantiation), while AR is focused on using research findings to improve a specific situation or problem. Participatory case studies do not require the same level of dual commitment and allow for a clearer outsider perspective. Additionally, a participatory case study is typically conducted in a single phase, with the researchers and participants collaborating to develop and implement the research. In contrast, action research is typically conducted over multiple cycles, with each cycle involving a new round of planning, action, observation, and reflection.

In this PhD thesis, multiple case studies (Yin, 2003) participatory research was employed to evaluate the GPM in the first cycle of DS-II, to collect the instantiation actions and challenges (DS-I in C2), and to draw more generalisable conclusions about the instantiation process in capital goods manufacturing companies.

3 Summary of Research Findings

This chapter presents the results of this PhD thesis alongside the related reflection. It is structured to first address the RC findings as an introduction to the results (Section 3.1), and then follow the DS-I, PS, and DS-II findings in the three DRM cycles, respectively.

The first cycle (C1) is related to the GPM for early-stage sustainable PSS design and is described in Section 3.2, the second cycle (C2) is about the GPM instantiation (Section 3.3), and the third cycle (C3) deals with the PSS concept sustainability screening (Section 3.4). While this chapter provides a brief description of key results and their relation to the RQs and research gaps, the detailed results are available in the Appended publications at the end of the thesis.

3.1 Research clarification – PSS drivers and barriers

This section brings forward the summarised results of the RC. Although the pivotal purpose of the RC is to define realistic and worthwhile research goals that can be achieved within the available project timeframe, the RC in this research also involved an exploratory literature review and a case study which yielded a result constitutive to the objective of this thesis. Namely, the result notably contributed to addressing the **first research question**[1] and partly bridging the **research gap A**[2].

The details of the results condensed in this section are available in the Appended Publication 1:

Sarancic, D., Pigosso, D.C.A., and McAloone, T.C. (2021), "Sustainability driven Product-Service Systems development: a case study in a capital goods manufacturing company", KES-SDM 2021 Conference, Vol. 262 SIST, Springer Singapore, pp. 1–11. doi:10.1007/978-981-16-6128-0_1.

PSS have the potential to bring forth plenty of benefits for the providers, customers, users and other involved parties in the network of actors. Naturally, the actors strive to capitalise on as many benefits as possible, which drive PSS development. However, trade-offs need to be made when prioritising the drivers, both within the primary PSS providers' companies and between all the companies involved in the network. The drivers determine the "why" of every actor, starting from the strategic and all the way to tactical and operational levels. Depending on the priorities the actors set, the accompanying barriers could thwart the development of the offering in practice and the full realisation of the benefits.

In total, 37 drivers and 45 barriers were identified in the literature and empirically through a case study in a capital goods manufacturing company that followed an exploratory literature review (Sarancic *et al.*, 2021a). A distinct reverse pattern was observed in the number of drivers and barriers when categorising them in relation to the different levels of the organisation: strategic, tactical, and operational (Figure 5). Based on the 360-degree approach around the case manufacturing company, more drivers were found at a higher, strategic level, whereas more barriers occur at tactical, and especially operational levels. This incongruity is especially relevant in the early-stage PSS design, as it is fairly straightforward to imagine strategic benefits at the outset of the strategic planning but challenging to foresee operational barriers down the road. Therefore, it is crucial to agree early on the priorities and drive the PSS design process in that direction.

The empirically identified drivers and barriers were largely consistent with the literature findings previously mapped by Sarancic et al. (2021b), where eight new drivers and five new barrier perspectives were mapped through the case study. While the drivers known from the literature revolved around the strategic level and the potential of PSS to create new business opportunities, switch to more environmentally sustainable practices, and secure aftermarket control, the barriers were largely tactical and operational such as the limited knowledge of pricing mechanisms, the total

[1] RQ1: What are the drivers and barriers for manufacturing companies to introduce PSS offerings?

[2] Gap A. The dispersion of the multi-disciplinary PSS research field and **the multitude of motivating and prohibiting factors** to introduce PSS offerings.

cost of ownership, and the lack of customer willingness to share production information, respectively. The newly identified drivers and barriers were likewise largely tactical and operational, due to the ability to dive deeper into the case company empirically. The new drivers related to being able to learn more about wear and tear parts, warranty cases, and how to best standardise the product portfolio. The new barriers identified empirically, on the other hand, included the lack of knowledge on the use period of the equipment, especially in terms of the operator's daily behaviour, how trained are the operators at the customer, and how the equipment performance changes over time.

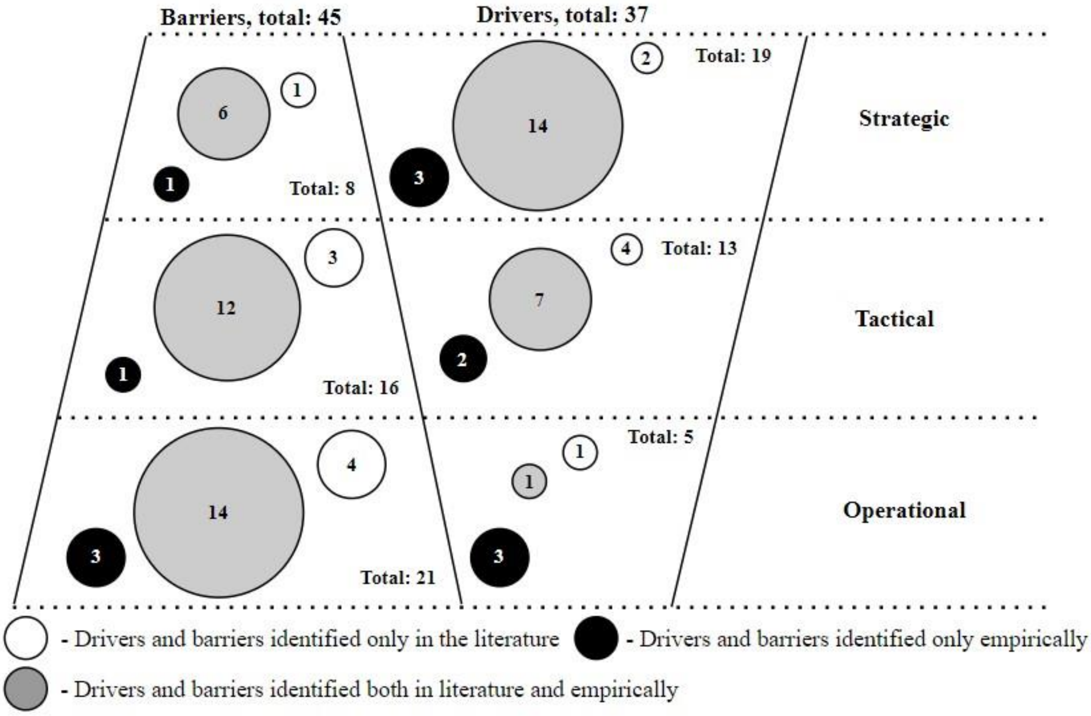

Figure 5. The number of PSS drivers and barriers identified (Sarancic et al.*, 2021b).*

The study also showed that the different parts of the manufacturing company had different perceptions of the drivers and barriers, both in terms of their technical and non-technical backgrounds and seniority levels. Hence, this business-wide investigation proved fruitful to (i) understand the interaction within the organisation, (ii) communicate the ideas across different departments and functions, and (iii) comprehensively explore all the opportunities and challenges by capitalising on the collective knowledge of the company because all internal actors will be impacted by the introduction of PSS.

This driver and barrier exploration in the RC concluded the first part of the research in the thesis by revealing the long-term and strategic importance of awareness of manufacturing companies about the complexity of the PSS design at the outset of the planning stages, which needs to be harnessed with a structured process. Therefore, the RC paved the way for laying out the GPM in C1, where motivation and expected challenges should be discussed in the initial decision-making node (gate) of the process.

3.2 Cycle 1 – GPM for early-stage sustainable PSS design

This section presents the summarised results of the first cycle (C1) of DRM. The first cycle accounts for a large part of the descriptive contribution of this thesis by addressing the **second research**

question[3] and its sub-questions. C1 addresses the remaining portion of **research gap A**[4], partially tackled in Section 3.1, fully bridges the **research gap B**[5], and fractionally covers the **research gap D**[6].

C1 included comprehensive DS-I and PS studies, as shown in Figure 4, available in detail in the Appended Publication 2:

Sarancic, D., Pigosso, D.C.A., Pezzotta, G., Pirola, F. and McAloone, T.C. (2023), "Designing sustainable product-service systems: A generic process model for the early stages", Sustainable Production and Consumption, Elsevier, Vol. 36, pp. 397–414. doi:10.1016/j.spc.2023.01.020.,

and a DS-II study available in detail in the Appended Publication 3:

Sarancic, D., Pigosso, D.C.A., and McAloone, T.C. (2023), "Evaluation and instantiation of a generic process model for early-stage sustainable Product-Service System (PSS) design within three manufacturing companies", (Manuscript under review at the Journal of Cleaner Production).

Key DS-I and PS findings in C1 are detailed in AP2 and directly relate to the sub-questions RQ2.1[7], RQ2.2[8], and RQ2.3[9], while the DS-II findings detailed in AP3 relate to sub-question RQ2.4[10].

3.2.1 Cycle 1 – DS-I results

The complete list of 96 identified and analysed multidisciplinary approaches with brief descriptions and other descriptive findings relevant to early-stage PSS design can be examined in Appendix A – Descriptive findings of the systematic literature reviewand also accessed at: https://doi.org/10.1016/j.spc.2023.01.020 as supplementary material of AP2.

The approaches to early-stage PSS design (i) focus on a variety of entities denoted with different terminology, (ii) stem from different subject areas, namely engineering and design (55), business management (22), and information systems (19), and (iii) embed TBL sustainability, CE, and life cycle considerations to divergent extents.

Out of the 96 identified approaches, eight were considered comprehensive when distilled with respect to four predefined criteria (C1. Focus on sustainability, C2. Validated industrial applicability, C3. Level of detail in terms of all the entities considered, and C4. Number of citations in the literature), but none generically applicable or with a clear process. Although different in scope, content, and terminology, the eight approaches exhibited similarities enabling the generalisation of the three critical phases in early-stage PSS design. Namely, (i) strategic planning, (ii) exploring opportunities, and (iii) PSS concept development, the content of which can be studied in depth in AP2.

Based on the extensive systematic literature review, the entities considered in all 96 approaches were clustered in seven overarching clusters: business model, the network of actors, requirements, functions, offerings, structure, and the plan for implementation. All the entities in the above clusters can be designed following a predefined workflow throughout the three phases consisting of five activities: identification, analysis, definition, selection, and refinement. Numerous tools were identified in the literature to support the design of individual entities or clusters of entities, such as

[3] RQ2: How to systematise the existing perspectives on early-stage PSS design in literature to develop a generic process model (GPM) for capital goods manufacturing companies?

[4] Gap A. **The dispersion of the multi-disciplinary PSS research field** and the multitude of motivating and prohibiting factors to introduce PSS offerings.

[5] Gap B. Lack of comprehensive and generic structured approaches to the early-stage PSS design.

[6] Gap D**. Lack of sustainability considerations** and structured ex-ante sustainability evaluation approaches for early-stage PSS design.

[7] RQ2.1: What are the existing approaches for early-stage PSS design in the literature?

[8] RQ2.2: What are the main phases, activities, tools, and constituent entities in the existing approaches to early-stage PSS design?

[9] RQ2.3: What are the sustainability considerations in the existing early-stage PSS design approaches and how to incorporate them into the GPM?

[10] RQ2.4: What is the usefulness and usability of the GPM within capital goods manufacturing companies?

the business model canvas (BMC), quality function deployment (QFD), or MECO (material, energy, chemical, and other) matrix, which are mapped according to their relevance to be used when tackling the design of particular entities, and in the correct phases.

The existing approaches deficiently included sustainability considerations or did not enable their inclusion due to the deficient structure of the approaches. For that reason, the sustainability considerations were mapped to be used later as a constitutive layer of the GPM in the relevant phases of the process and when designing different clusters of entities.

3.2.2 Cycle 1 – PS results

Based on the above summarised DS-I results, a GPM for early-stage sustainable PSS design was devised (Figure 6). The GPM translates decades of multidisciplinary research into an industrially actionable yet very comprehensive process to support companies in creating or instantiating their processes for the development of more effective and sustainable PSS. It contributes both to the conception of the structure of a generic process model for early-stage PSS design and as a reference model in the knowledge domain, at the same time enabling the inclusion of various sustainability considerations in the process.

The GPM was conceived to consist of temporal (three phases) and content dimensions (seven clusters) in a stage-gate form based on the Rational Unified Process (RUP) (Kruchten, 2000), and the functional modelling language IDEF0 (ICOM notation) (ISO 31320-1, 2012), to promote its adoption among manufacturing companies, where such structures are already used in various business processes (Aguilar-Savén, 2004).

The process model has been developed to highlight the sequential order of activities and entities that require focused attention from manufacturing companies at each stage of the process. Trapezoids are utilised in the model to signify the particular entities that are the focus of each stage. For instance, during the strategic planning stage, attention should be given to the business model and the network of actors such as customers, partners, competitors, suppliers, and institutions. Although the clusters in the model may seem discrete, in reality, they are interdependent and require multiple iterations and feedback loops when using the process model. Gates are incorporated in the process model to serve as checkpoints, where decision-makers should evaluate the quality of the previous stage and make decisions on whether to proceed to the next stage.

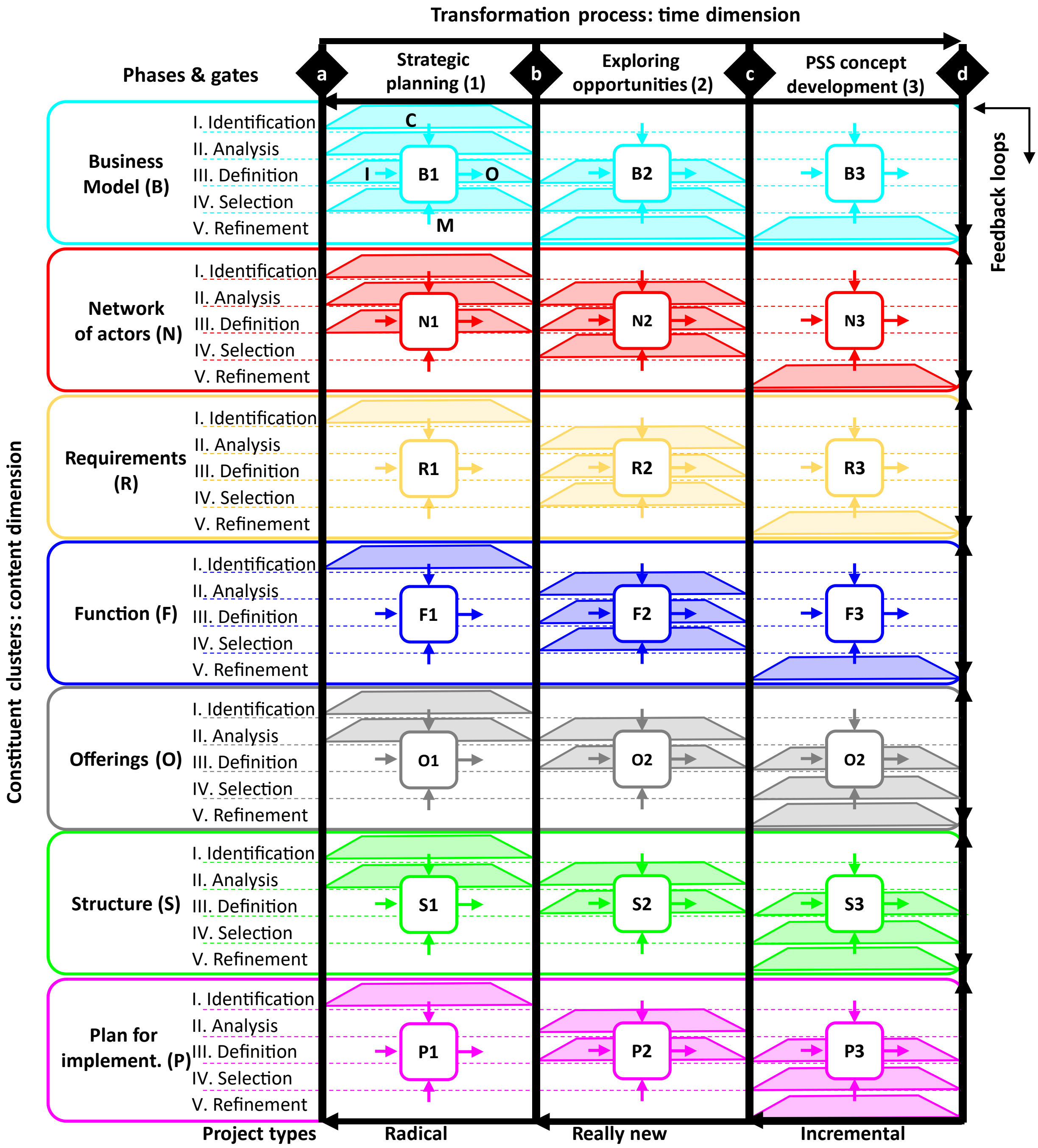

Figure 6. The GPM for early-stage sustainable PSS design (Sarancic, Pigosso, Pezzotta, et al.*, 2023).*

3.2.3 Cycle 1 – DS-II results

The theoretically developed GPM was systematically evaluated concerning eight predefined criteria (utility, consistency, completeness, scope, broadness, precision, simplicity, and clarity) by the employees (14) of three capital goods manufacturing companies. The participating employees in each company attempted to use it for the creation of their PSS design process through the instantiation of the GPM throughout three overlapping six-month periods and then started executing the process. These GPM applications, even though limited to three companies, showed promise for successful industrial use. The evaluation concerning each criterion is detailed in AP3, where the initial steps for the GPM's evaluation were already paved the AP2, as well as in Supplementary Publication 7 (Sarancic, Sánchez Díez, Pigosso and McAloone, 2023).

Given that the new PSS offering development might take several years depending on the company's context, a longitudinal study would be necessary to report on the success of every phase of the GPM execution, regarding the offering's success on the market. Therefore, such an evaluation is out of the scope of the thesis. However, the complete GPM has been executed in the primary case company to develop PSS concepts. These results are confidential, as they are yet to be realised and released to the market but they show promise of success and the company is moving towards their implementation in practice.

The representatives of the three industrial companies unanimously regarded the GPM particularly highly with respect to its utility, consistency, and broadness, while the lack of simplicity was considered as a criterion hindering immediate actionability and implementability in their companies, indicating the well-known mismatch in abstraction between industry and academia. All the companies agreed that the introduction of such a process (instantiated to their contexts) is necessary and valuable but requires tremendous changes in the organisation, which might slow down and complicate the adoption. For that reason, the next cycle of research (C2) focused on the instantiation guidelines intended to alleviate the GPM adoption challenges and support companies in reforming the way they look at value creation.

3.3 Cycle 2 – GPM instantiation guidelines

This section showcases the summarised results of the second cycle (C2) of DRM. The second cycle addresses the **third research question**[11], with a sharp focus on closing the **research gap C**[12]. C2 included DS-I and PS studies, as shown in Figure 4, available in detail in the Appended Publication 3:

Sarancic, D., Pigosso, D.C.A., and McAloone, T.C. (2023), "Evaluation and instantiation of a generic process model for early-stage sustainable Product-Service System (PSS) design within three manufacturing companies", (Manuscript under review at the Journal of Cleaner Production).

Key DS-I findings in C2 directly relate to the sub-questions RQ3.1[13] and RQ3.2[14], while the PS findings answer the overarching RQ3. As described in Section 2.1.4, a formal DS-II study was not utilised in C2 of this thesis, since the evaluation of the GPM instantiation guidelines occurred concurrently during their participatory empirical development.

This cycle of research was guided by the particular hypothesis elaborated in AP3 that the GPM can, in fact, be instantiated to company-specific process models and support them in systematically and repeatedly designing PSS offerings for sustainability.

3.3.1 Cycle 2 – DS-I results

The descriptive results in this cycle are mainly empirically founded and obtained through the attempts to apply and instantiate the GPM in the three equipment manufacturing companies, as detailed in Appended Publication 3. Each of the companies undertook a series of action steps in order to tailor the GPM to their context, and this research focused on recording and interpreting those actions to better understand how to support the future adoption of the GPM in manufacturing companies. Therefore, the DS-I study in C2 consists of the (i) mapped actions the three companies took to instantiate the GPM and (ii) the challenges they encountered along the way.

The three companies undertook (10-11) instantiation actions covering 15 themes which were relatively similar between the companies, however, some differences were observed, stemming from

[11] RQ3: *How to enable the application of the GPM in practice to support PSS design in capital goods manufacturing companies?*

[12] Gap C. Lack of industrially implementable approaches and guidelines to support PSS adoption by manufacturing companies.

[13] *RQ3.1: What are the actions the capital goods manufacturing companies took to instantiate the GPM to their specific contexts?*

[14] *RQ3.2: What are the challenges the capital goods manufacturing companies encountered during the GPM instantiation? What are the challenges during the GPM instantiation process in capital goods manufacturing companies?*

the sizes of the companies and the disparate industries they operate in. All companies spent a significant amount of time familiarising themselves with the terminology of the GPM and cross-comparing it with their existing processes for either product or service design. A fair amount of attention was dedicated to further compartmentalisation of the process into a form that resembles the organisational structure of the companies, even though all acknowledged the need for a cross-departmental and multi-function process. Sustainability considerations were judged differently by the companies, where smaller companies saw them as an add-on, and the largest of the three saw it as an integral part of the PSS business case.

Fifteen distinct challenge themes were identified during the instantiation attempts by the companies, which can also be seen as headlines of the 15 steps in the instantiation guidelines (Figure 7). Most of the challenges were present in all three companies, irrespective of the size and their industry. Challenges to particularly point out are (i) the difficulty of mapping the information and communication flows between the large internal and external actor networks in terms of the timing and the content necessary to be conveyed, (ii) the lack of awareness of the connection between PSS and sustainability, and (iii) the uncertainty of the early-stage PSS design where it is exacting to judge whether the execution is going well until far into the process.

3.3.2 Cycle 2 – PS results

Building on the results of DS-I, i.e., the actions companies undertook and the challenges they encountered, consolidated instantiation guidelines for the GPM in manufacturing companies were proposed (Figure 7). The guidelines represent a sequential course of action when tailoring the GPM to the specific context of individual manufacturing companies, which is deemed to increase both the adoption rate and speed.

This second cycle of DRM, namely the instantiation guidelines, enables the GPM adoption in its context-specific versions by the companies and thereby supports them in designing potentially more sustainable PSS concepts in a structured way. The actual sustainable potential of those PSS concepts is to be determined through a screening process, which is enabled by the screening tool developed in the third cycle in the next section.

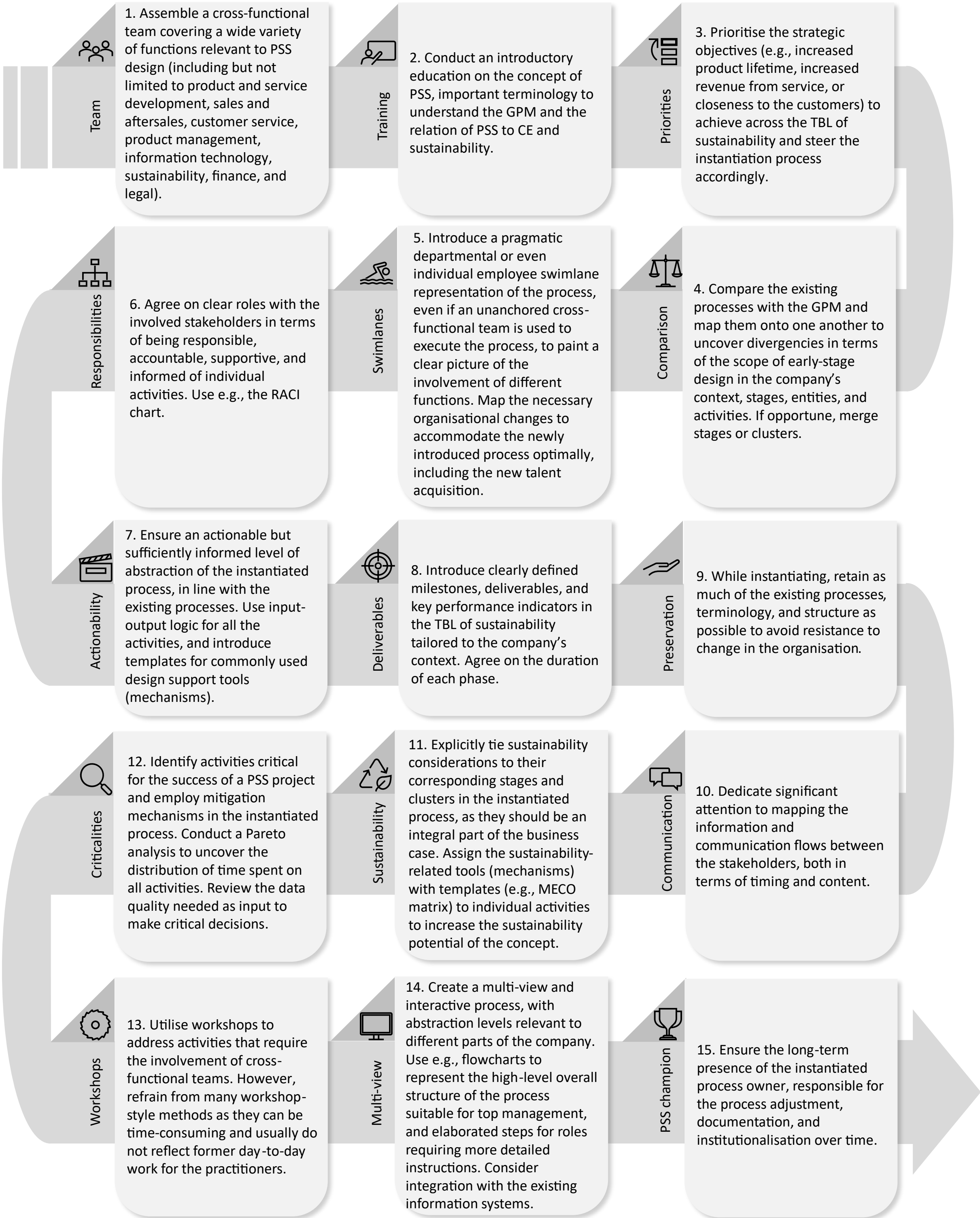

Figure 7. GPM instantiation guidelines (Sarancic, Pigosso and McAloone, 2023, forthcoming).

3.4 Cycle 3 – PSS concept sustainability screening (BESST)

This section introduces the summarised results of the third cycle (C3) of DRM. The third cycle addresses the **fourth research question**[15] and fully closes the **research gap D**[16] initially tackled in C1. C3 included DS-I, PS, and DS-II studies, as shown in Figure 4, available in detail in the Appended Publication 4:

Sarancic, D., Pigosso, D.C.A., Colli, M., and McAloone, T.C. (2022), "Towards a novel Business, Environmental and Social Screening Tool for Product-Service Systems (BESST PSS) design", Sustainable Production and Consumption, Elsevier, Vol. 33, pp. 454–465. doi:10.1016/j.spc.2022.07.022.,

and the Appended Publication 5 which further focuses on the DS-II (evaluation part) in the third cycle:

Sarancic, D., Metic, J., Pigosso, D.C.A. and McAloone, T.C. (2023), "Impacts, synergies, and rebound effects arising in combinations of Product-Service Systems (PSS) and circularity strategies", Procedia CIRP, Vol. 116, pp. 546–551. https://doi.org/10.1016/j.procir.2023.02.092.

Key DS-I, PS, and DS-II findings in C3 directly relate to the sub-questions RQ4.1 and RQ4.2[17], RQ4.3[18], and RQ4.4[19], respectively.

The main result of C3, obtained through three cycles of action research, is the novel business, environmental, and social screening tool (BESST) for PSS concepts.

3.4.1 Cycle 3 – DS-I results

The descriptive output of this cycle was (i) the overview of nine relevant PSS evaluation approaches identified through a literature review, (ii) the systematisation of dimensions necessary for comprehensive ex-ante sustainability screening of PSS concepts, and (iii) the success criteria to be satisfied with the support tool to be developed in the PS part of the cycle.

The nine approaches identified in the literature all had their strong sides and shortcomings, but none was considered complete with respect to all the relevant dimensions nor fully suitable to satisfy the success criteria brought forward by the case company. Some of the approaches identified in the literature neglected the value perspectives, some allowed only for ex-post evaluation, while others disregarded the social dimension of sustainability or the life cycle perspective.

The case company required six success criteria to be satisfied with the tool, relating to (i) alignment with the TBL-based corporate strategy, (ii) support in decision making, (iii), ex-ante perspective at a conceptual level, (iv) quick and straightforward usability, (v) clear visual communication, and (vi) the primary focus on the provider' perspective on value.

After a thorough analysis of various PSS definitions and the existing PSS evaluation tools, the necessary four key dimensions for successful PSS concept sustainability screening were distilled and defined as (i) PSS elements including the product, service, network, and infrastructure, (ii) TBL sustainability denoting the stability the economic, environmental, and social capitals, (iii) life cycle perspective consisting of three phases (Beginning-of-Life (BoL), Middle-of-Life (MoL) and End-of-Life

[15] *RQ4:* How to systematise the existing perspectives on PSS concept sustainability to develop a sustainability screening tool for PSS concepts?

[16] Gap D. Lack of sustainability considerations and **structured ex-ante sustainability evaluation approaches** for early-stage PSS design.

[17] *RQ4.1: What are the existing approaches for PSS concept sustainability evaluation? RQ4.2: What are the key dimensions to consider in ex-ante PSS concept sustainability screening?*

[18] *RQ4.3: How to identify TBL benefit and cost hotspots of a PSS concept?*

[19] *RQ4.4: What is the usefulness and usability of the sustainability screening tool for PSS concepts within capital goods manufacturing companies?*

(EoL)), and (iv) value defined as benefits versus sacrifices perceived regarding the impact of the PSS concept.

3.4.2 Cycle 3 – PS results

The descriptive findings were unified in a comprehensive yet readily applicable four-dimensional tool for ex-ante PSS concept screening which enables the identification of positive and negative hotspots of any PSS concept (Figure 8). Thereby, extending and further detailing previous attempts to formulate multi-dimensional evaluation tools for sustainability-oriented innovation (Hansen *et al.*, 2009), but sharply focused on assessing the early-stage PSS design concepts.

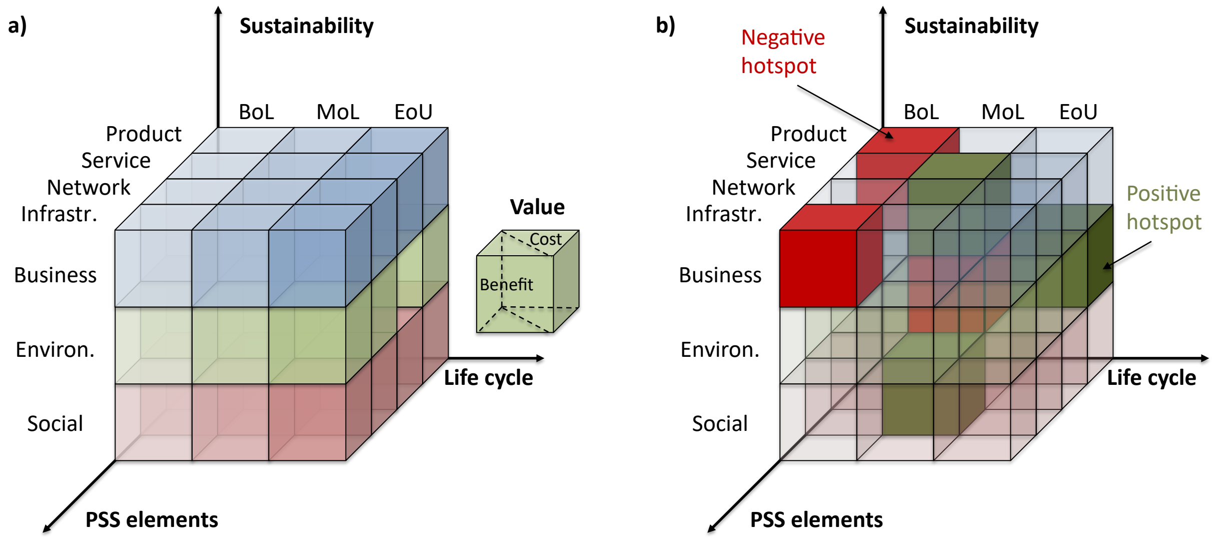

Figure 8. a) The BESST cube, b) An example of hotspot identification (Sarancic et al.*, 2022).*

As shown in Figure 8, PSS concepts can be represented by 36 dice forming the BESST cube, where the cube contains a total of 72 data points describing the benefits and costs of each dice of the concept to form an all-encompassing picture of its impact.

Alongside the BESST tool, an implementation process consisting of eight steps was devised to ease the tool use in a workshop setting, which is explained in detail in Appended Publication 4 and depicted in Figure 9.

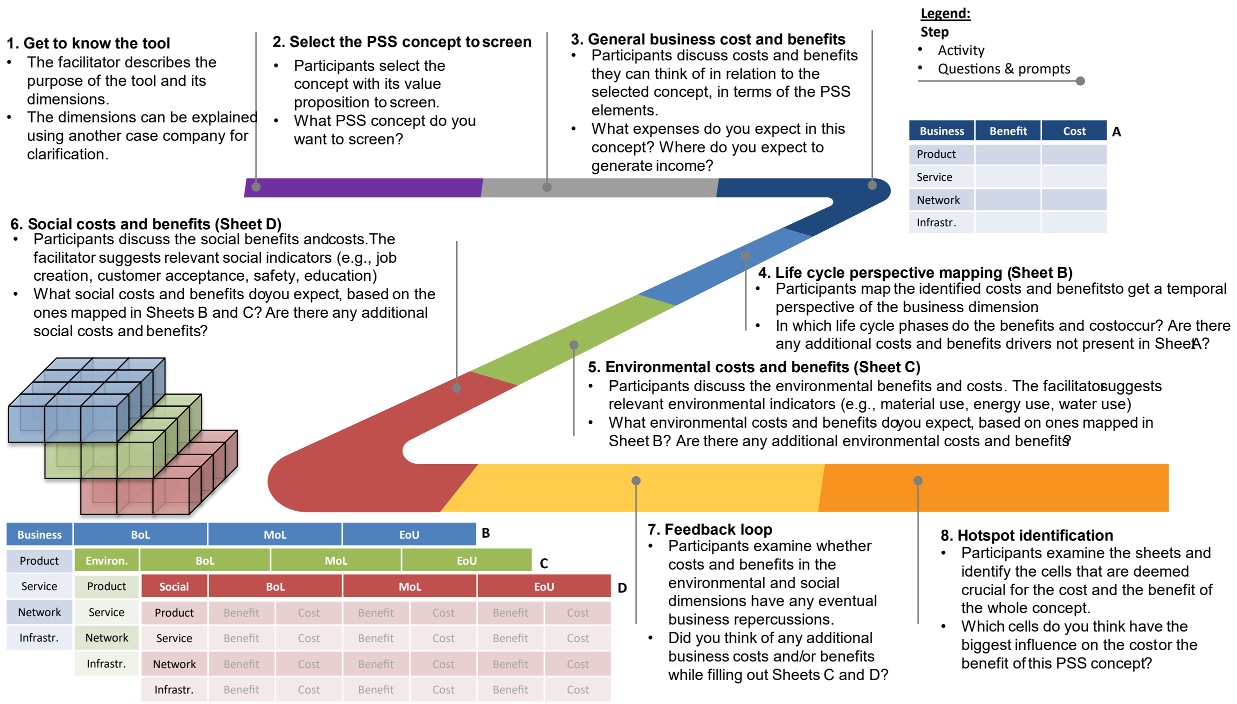

Figure 9. BESST implementation process (Sarancic et al.*, 2022).*

3.4.3 Cycle 3 – DS-II results

The BESST was iteratively improved through three AR cycles of exposure to academic and industrial experts, each time incorporating the feedback received into the new version. In the first AR cycle, the feedback revolved around the definitions of the provider's life cycle perspective and the TBL interpretation. In the second AR cycle, all the definitions of the elements were further summarised and clarified for easier use, and the implementation process was further streamlined. In the final, third AR cycle, extra examples to facilitate workshop discussion were included and usability questions that arose in the industrial setting workshop were incorporated into the final version of the tool.

The BESST was also quantitatively evaluated in the second AR cycle, where the workshop participants gauged the feasibility, usability, and utility of the tool through a test of different implementation processes. Thereby, enabling the selection of the optimal process (Figure 9). The final version of the BESST was compared to the nine existing approaches identified as relevant, with respect to the success criteria brought forward by the company and the four key dimensions identified in DS-I of C3.

The BESST tool was further utilised for ex-ante analysis of the impacts i.e., identification of positive and negative hotspots arising in seven combinations (configurations) of different PSS types defined by Tukker (2004) combined with other circular strategies (rethink, reduce, upgrade, reuse, repair and maintain, refurbish, remanufacture, and repurpose). In this application, the tool proved useful and suitable for providing a quick but exhaustive insight into the TBL cost and benefits drivers of every concept. Therefore, indicating BESST's potential to be used not only strictly for PSS concepts but perhaps also to screen the impacts of different sustainability-oriented business development initiatives. More details of this study can be found in Table 1 for each of the seven colour-coded configurations, as well as in the Appended Publication 5.

Table 1. Seven configurations analysed with the BESST (Sarancic, Metic, Pigosso and McAloone, 2023).

Config.	Configuration description	Positive hotspots (benefits)	Negative hotspots (costs)

			Coord. (BESST)	Description of main benefits	Coord. (BESST)	Description of main costs
1.		Sell products and time-limited contracts including repair, maintenance, and spare parts to ensure greater product availability, and optimal operation and energy use. Benefits and costs both manifest mainly in MoL due to increased service activities.	Business-MoL-Service	Additional revenue stream	Business-MoL-Service	Risk of variable costs
			Environ.-MoL-Service	Less energy use, prolonged life	Environ.-MoL-Service	More travel, i.e. pollution
			Social-MoL-Service	More customer touchpoints	Social-MoL-Network	Loss of internal service jobs at the customer
2.		Sell products and monitoring equipment to get data about product use. Provide advice, training, updates, and upgrades based on data. Benefits manifest through increased knowledge sharing and data-based actions. Costs incur mainly in BoL to establish the monitoring infrastructure and acquire data analytics capabilities.	Business-MoL-Infrastr.	Getting use insights for future development	Business-BoL-Infrastr.	Cost of monitoring equipment
			Environ.-MoL-Product	Enable optimised use due to monitoring	Environ.-MoL-Infrastr	More energy is spent on monitoring
			Social-MoL-Network	Trained personnel at customers	Social-MoL-Network	Customers afraid to share data
3.		Lease product and take responsibility for monitoring, preventive maintenance and repair. Benefits similar to the above configurations, but also evident through stable subscription revenue over time. However, costs and risks are introduced with additional responsibility as well as investment into product ownership retention.	Business-MoL-Service	Predictable, recurring revenue	Business-BoL-Product	Cost of ownership retention
			Environ.-BoL-Product	More intensive use by the customer to make the most of the lease	Environ.-BoL-Product	Building more material-intensive (robust) product
			Social-MoL-Service	Fewer injuries because professionals do the service	Social-MoL-Network	The intensity of work increases for service employees
4.		Repeatedly rent several products. Restore the products and their parts between the rents. Benefits manifest through the flexibility of offering in terms of scalable capacities when needed, new markets, and lower access bar. Costs incurred due to increased	Business-BoL-Network	New markets open for smaller customers or seasonal production	Business-BoL-Infrastr.	Build additional storage, workshops and tools
			Environ.-MoL-Infrastr.	Infrastructure can be shared for many products.	Environ.-EoL-Service	Increased logistics operations

		logistics and initial infrastructure investments to handle the more frequent turnover of products.	Social-BoL-Network	Lowering access bar for customers	Social-EoL-Network	Hygienic challenges when changing users
5.		Instal products at a customer and charge according to the use level. Take responsibility for monitoring and preventive maintenance and repair. Many shared benefits with config 3. Moreover, benefits through the ability to streamline product operation according to customer needs and ensure customer lock-in. Costs due to the complexity of monitoring and pricing schemes, and difficulty in predicting earnings.	Business-MoL-Service	Recurring revenue	Business-MoL-Service	Difficult to predict revenue
			Environ.-MoL-Service	Streamlined product operation	Environ.-MoL-Service	More service operations to keep the product running optimally
			Social-MoL-Network	Longer lasting relationships	Social-MoL-Network	Possible lack of trust from customers due to feeling of being surveilled
6.		Find third-party service providers to cover upgrades, repairs, refurbishment, and remanufacturing. Benefits due to rapid increase in market share coverage through partnership and opportunities to gain insights into more customer operations. Costs due to increased relationship management and possible distancing from customers because of the third party in between.	Business-BoL-Network	Secure more projects because of expanded capabilities	Business-MoL-Service	Losing a part of the service business
			Environ.-EoL-Product	Use products and parts that would otherwise go to waste	Environ.-MoL-Network	More pollution due to inefficiency in ecosystem coordination
			Social-BoL-Network	Form external partnerships and get knowledge from them	Social-MoL-Network	The burden of partnership coordination
7.		Agreement to deliver a result to the customer, regardless of the product used. Benefits stem from a high level of offering customisation which enables higher margins. Costs can be incurred due to unforeseen overheads, risks and an increase in responsibilities to deliver the total solution on time.	Business-MoL-Service	The highest profit margins	Business-BoL-Infrastr.	The large initial investment to ensure product performance
			Environ.-MoL-Product	Flexibility to combine less impactful modes to get results	Environ.-BoL-Infrastr.	All the infrastructure to support (many) offerings has to be built
			Social-BoL-Network	Eliminated unnecessary communication with customers	Social-MoL-Network	Stressful for employees due to expected performance

4 Discussion and reflection

This chapter explains how the individual results conjointly fulfil the overall objective of this PhD thesis (Section 4.1), and more broadly reflects on the research findings summarised in the previous chapter and detailed in the five appended papers (Section 4.2). Further, it relates the key results to each research question (Section 4.3), brings forward the limitations of this research (Section 4.4), and provides suggestions for future research (Section 4.5).

4.1 A systematic framework for early-stage PSS design for sustainability

In addition to the standalone results stemming from the RC (Section 3.1), and the three cycles of DRM (C1, C2, and C3, Sections 3.2-3.4), this PhD thesis proposes a systematic framework for early-stage PSS design for sustainability (Figure 10) that unifies the four individual results into a comprehensive whole. This framework is considered the main vessel to fulfilling the objective[20] of this PhD thesis.

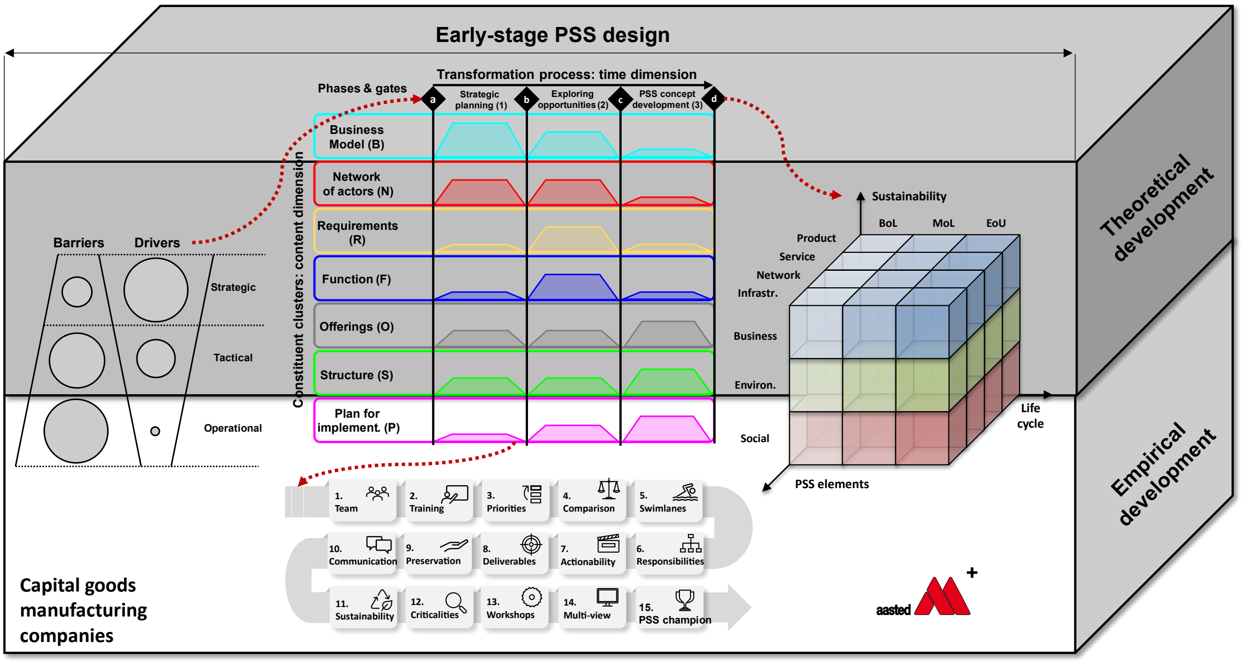

Figure 10. Consolidated result and the red thread of the PhD thesis.

The framework provides structured decision-making support for the managers within manufacturing companies in the early-stage PSS design for sustainability based on rigorous theoretical and empirical studies conducted in an alternating and complementary manner.

The framework enables practitioners from both academia and industry to:

1. Examine their drivers to introduce PSS as part of their offering portfolio while being fully informed of barriers they can expect. This knowledge is considered strong support in determining the 'why' and steering the PSS design process according to the a priory set direction starting from the first gate ("a") of the GPM, as well as to align with the overall corporate strategy.
2. Structure their early-stage PSS design process with the help of the GPM which contains all the necessary design knowledge, the sequence of activities to design promising PSS concepts, and accompanying sustainability considerations.

[20] Develop a systematised framework to support managers in early-stage PSS design for sustainability in capital goods manufacturing companies.

3. Increase the chances and the speed of successful implementation of the instantiated versions of the GPM with the help of the consolidated instantiation guidelines which bridge the inherent disparity between theoretically envisioned generic process models and the industrially pragmatic process models in manufacturing companies.
4. Quickly but comprehensively screen the various PSS concepts at the end (gate "d") of their GPM-based process models with respect to TBL sustainable value over the complete life cycle of the offerings concerning the four main PSS elements with the BESST.

Therefore, the above-described points conjointly construct the systematic framework for early-stage PSS design for sustainability together with the much-needed instructions on how to instil it into the practical industrial context of a manufacturing company. It has to be noted that the four principal results forming the framework can be used independently of each other. For example, the PSS concept does not need to be designed strictly with the support of the instantiated GPM in order to be able to screen it with the BESST.

4.2 Reflection on the results

This reflection aims to critically analyse the framework proposed in the PhD thesis, delving into its merits and challenges. This analysis will emphasise self-critique, identification of contradictions, and comparisons to established frameworks in adjacent fields to PSS, such as Cooper's stage-gate model (Cooper, 1990, 2008, 2014). The overarching goal is to ascertain whether this framework has the potential to address the historical shortcomings of previous attempts and contribute substantially to the transition to structured PSS design for sustainability.

The development of a systematic framework for early-stage PSS design for sustainability marks a significant step in the pursuit of sustainable practices within capital goods manufacturing companies. The framework shows great promise as it encourages businesses to adopt a proactive stance towards sustainability, rather than merely mitigating negative impacts retroactively. It fosters visionary thinking by promoting the PSS design that can transform entire companies and consequently industries, thus redefining how products are perceived and consumed. However, contradictions arise concerning the implementation of sustainability-motivated initiatives alongside business objectives. Striking a balance between environmental sustainability and profitability can be challenging (Tenucci and Supino, 2020), potentially leading to compromises that diminish the overall impact of the framework, as environmental or social sustainability considerations could be disregarded throughout the design process. The emphasis on long-term sustainability goals might not always align with short-term financial expectations, posing a risk to the viability of its adoption and sustained utilisation by companies. On the other hand, the development of such frameworks might also nudge companies' management to readjust shorter-term planning with more TBL-sustainable solutions.

Comparing the proposed systematic framework to Cooper's stage-gate model (one of the most widely applied models within product development in industry), several points of convergence and divergence can be identified. Cooper's model's success lies in its structured approach to product development, to which companies are accustomed, and ought, therefore, to accept more easily. However, stage-gate models often prioritise the conventional iron triangle of cost, quality, and time objectives over environmental and social aspects (Chawla *et al.*, 2018). On the contrary, the systematic framework presented in this thesis emphasises TBL sustainability from the outset, therefore, providing a platform to shift priorities but still in a familiar, stage- and gate-bounded manner.

Nonetheless, the key shortcomings of a stage-gate model are its rigidity and sequential nature, where radical innovations such as PSS design possess distinctive characteristics that overwhelm the capabilities of stage-gate models (Bers *et al.*, 2014). Sequentiality can slow down innovation processes, making it difficult for companies to adapt swiftly to emerging sustainability challenges and evolving requirements. The proposed framework, if implemented successfully, could mitigate this slowness by integrating sustainability considerations from the initial stages of PSS design, iterativeness in execution, or best yet, its instantiation into more dynamic platforms that can accommodate the necessary occasional process changes.

Over the years, there have been numerous attempts to implement sustainability measures in PSS design. Many of these attempts failed due to a lack of clear frameworks, insufficient integration of sustainability aspects, and the absence of a comprehensive approach that considers all relevant dimensions. The pace of overall advancement in generic PSS design for sustainability appears to be notably slower than anticipated by McAloone and Pigosso (2017), and no particular research avenues have thus far led to a complete framework. The research by Brissaud et al. (2022) emphasises that the underlying cause for this phenomenon lies in the inherent complexity of design objects and their requisite design processes, which are profoundly influenced by contextual factors, consequently, attaining the projected PSS design process standardisation becomes exceedingly challenging.

Brissaud's claims were considerably substantiated by the findings obtained in this thesis, primarily through empirical action research, where initial enthusiasm for PSS design process structuring quickly runs into pragmatic issues of daily operation and organisational structure at a company. This observation is in line with the well-known Dunning-Kruger effect (Dunning, 2011), where the practitioners soon realise their cognitive bias of overestimating their competence and underestimating the difficulty of implementing PSS due to the initially perceived similarity of the PSS design process with the existing product design processes at the company. This realisation of PSS design complexity slows the design process, forcing management to dedicate more resources to deliver on time, but also inherently further increasing complexity due to a larger network of actors being introduced. With the larger number of actors comes the growth of possible communication paths, therefore, it becomes increasingly important to design the communication structures, due to their potential to constrain the complexity of a system that the organisation can produce (a.k.a. Conway's law) (Conway, 1968). The same law, likewise, influences the instantiation process of the GPM, as the structure of the team selected to instantiate it will pose a constraint on the complexity of the instantiated version of the process, therefore supporting the idea that the organisation must develop and evolve (servitise) so that the PSS design process (and the PSS offering) could evolve (Sarancic, Pigosso, Pezzotta, *et al.*, 2023).

As argued in the same reference, PSS concepts are themselves perpetually evolving, and it is critical to determine optimal timing to either (i) lock-in certain concepts and exploit them further through incremental improvement projects (Garcia and Calantone, 2002) or (ii) engage in exploration through radical innovation or really new projects, as elaborated by March (1991).

Another hindrance to a successful implementation of PSS design for sustainability is that companies have often historically treated sustainability as an afterthought, rather than an integral part of the design process (Laszlo and Zhexembayeva, 2017), whereas the proposed framework can potentially put an end to these attempts by providing a structured process that fosters a holistic understanding of sustainability from the outset. This encourages companies to embed sustainability into their core values and design practices, thus facilitating genuine progress towards sustainability goals and a mindset shift urging them to embrace sustainable innovation and look beyond mere compliance.

Even though digitalisation is seen as one of the main enablers of servitisation and smart PSS (Pirola *et al.*, 2020; Zheng *et al.*, 2018), the absence of a significant focus on digital technologies, IoT (Internet of Things), smart connected products (SCP), big data, digital twins, and industry 4.0 concepts in this thesis can be attributed to several strategic considerations, as well as the context of the empirical setting. Beyond the necessary attention given to this aspect of PSS in the structure cluster of the GPM that elaborates on the support systems for enhanced delivery of value through supporting equipment, software, and sensors (Sarancic, Pigosso, Pezzotta, *et al.*, 2023), this research has not focused on the "smartness" of PSS further for several reasons.

Firstly, the core objective of this study primarily revolves around exploring principles of design for sustainability that minimise environmental impacts, promote resource efficiency, and extend product life. While digital technologies in servitisation of manufacturing can undoubtedly play a crucial role in optimising operations and resource allocation (Hallstedt *et al.*, 2020; Pagoropoulos *et al.*, 2017), their adoption may inadvertently shift the emphasis from ecologically conscious system design to operational efficiency. It also must be noted that sustainability gains achieved due to the use of digital technologies are often offset by the significant energy and material inputs required for their employment (Truong, 2022).

Secondly, the offering integration into cyber-physical systems can introduce complexities in terms of digital cross-organisational collaboration, data security, and interoperability (Kohtamäki *et al.*, 2019; Lu, 2017) which are outside the scope of this research and may divert attention from the fundamental goal of creating sustainable systems and avoiding the digital divide.

Furthermore, manufacturers in many industries can deliver PSS offerings with far superior TBL potential than traditional offerings without the use of digital technologies (Manzini and Vezzoli, 2003), not only because of the rebound effects digital technologies may cause. Once such PSS offerings are developed by companies, the created process knowledge can be then utilised as a foundation to pave the way for a structured approach to digitise their offerings, e.g., by moving from services accompanying products such as monitoring towards product control, optimisation, and autonomy services (Porter and Heppelmann, 2014). Such is the case of the primary collaborating company which operates in a slow-moving industry not yet particularly reliant on digital services.

Overall, by narrowing the focus of this research to the core of PSS design for sustainability, the aim was to provide a holistic understanding that can serve as a foundation upon which digital technologies can be integrated judiciously in future endeavours, ensuring that sustainability considerations remain at the forefront of the investigation.

It might also be useful to reflect on the use of the developed framework, especially the GPM, to structure education on PSS design. The author has encountered several courses dedicated to PSS design, on both Masters and PhD levels, throughout the duration of the PhD project. The common shortcoming of those courses was not a lack of tools, proposed to support PSS design, but a lack of connection between these, to aid decision-making in a PSS design process. Numerous tools exist that aim to support either product or service design under the umbrella of PSS, and fewer tools exist to support the design of the PSS's actor-network and infrastructure. However, it remains unclear how all those tools should interact with each other and how their outputs can be used as inputs to the next tool used in the design process. The GPM ameliorates that shortcoming by proposing an input-output structure of the process model and by proposing in which phases should different tools be used, thereby potentially introducing much-needed structure to the curricula of future PSS design education.

4.3 Research questions answered

This section serves to concisely answer the overarching research questions and relate the answers to the key results.

***RQ1**: What are the drivers and barriers for manufacturing companies to introduce PSS offerings?*

In Section 3.1, the knowledge available in the literature, as well as the newly empirically generated knowledge about the drivers and barriers for (capital goods) manufacturing companies to introduce PSS offerings were summarised. The 37 drivers and 45 barriers were systematised into three levels; strategic, tactical, and operational, in order to support the priority setting in PSS design, as well as to be able to anticipate or pre-emptively address the barriers. The case study with the newly empirically identified drivers and barriers is explained in detail in the Appended Publication 1, while the literature review identifying the already-known drivers can be examined in Supplementary Publication 6.

RQ2: *How to systematise the existing perspectives on early-stage PSS design in literature to develop a generic process model (GPM) for capital goods manufacturing companies?*

In Section 3.2, the systematisation of 96 existing approaches to PSS design has been succinctly presented and is available for detailed inquiry in the Appended Publication 2. In order to arrive at the stage where a generic process model can be proposed as a means of systematisation, a number of different types of analyses of the existing approaches had to be conducted in relation to: (i) temporal transformation process in terms of phases, gates, and the sequence of activities necessary to arrive at a methodically designed PSS concept; (ii) constituent entities and their clusters needed to be considered throughout the process; (iii) the structure of the process with the underlying RUP and IDEF0 characteristics; (iv) sustainability considerations to be made along the process; and (v) the different project types that can be supported by the GPM, alongside with the necessary feedback loops both in between the cluster entities and the phases of the model. Therefore, to create a generic process model such as the one proposed in this thesis, thorough research was necessary both to devise the meta-model, i.e., the structure of the process and the reference model with the generally applicable domain knowledge for early-stage PSS design for sustainability.

RQ3: *How to enable the application of the GPM in practice to support PSS design in capital goods manufacturing companies?*

In Section 3.3, viz. Appended Publication 3, the consolidated instantiation guidelines are proposed to enable the application of the GPM in practice. The guidelines were built based on participatory and case study empirical research in close collaboration with three equipment manufacturers, where the actions to adopt and adapt the GPM in individual contexts were recorded, and the challenges that appeared along the way were identified and addressed in the creation of the instantiation guidelines. The guidelines consist of 15 sequential actions covering 15 distinct themes a manufacturing company should undertake to increase the chances of successfully embedding the context-tailored GPM. The proposed instantiation guidelines heavily reinforce the importance of setting priorities and choosing battles prudently (drivers and barriers) when introducing PSS offerings and the PSS design process in a manufacturing company. The guidelines further stress the importance of cross-organisational collaboration, clearly defined communication channels and responsibility attribution, as well as the need to embed the sustainability consideration directly into the instantiated version of the GPM. The details about the proposed instantiation guidelines can be found in Appended Publication 3.

RQ4: *How to systematise the existing perspectives on PSS concept sustainability to develop a sustainability screening tool for PSS concepts?*

In Section 3.4, the summarised research findings are presented based on a comprehensive analysis of the nine most relevant approaches for PSS sustainability screening. The systematisation included the decomposition of the existing approaches and definition of the four necessary dimensions for successful ex-ante PSS concept sustainability screening, namely, TBL sustainability, PSS elements, life cycle perspective, and the value dimension. The development of the business, environmental, and social screening tool (BESST) was executed through three cycles of action research, where the need for the tool has been identified both in literature due to deficiencies in the existing tools and in the case manufacturing company which defined their requirements for the tool via six success criteria. The tool was iteratively improved after exposure to academic and industrial PSS experts and is accompanied by the eight-step implementation process tailored to a workshop setup. BESST enables companies to scrutinise different PSS concepts and identify positive and negative impact hotspots following an exhaustive investigation of 72 data points that describe the benefits and costs of different parts of a PSS concept.

4.4 Limitations

While this section discusses the overall limitations of the consolidated research result presented in Section 4.1, the detailed limitations of each of the four main results in this PhD thesis are detailed in the respective appended publications.

The principal challenge this research faces manifests in the discrepancy between academic and industrial measures of success of the research, where the generic nature of support is seen as an advantage and disadvantage, respectively. This discrepancy was mainly addressed by the creation of the GPM which can be tailored to specific contexts of manufacturing companies with the help of instantiation guidelines, thereby potentiating both general applicability and more customised adaptations. Tailoring the framework to suit the specific needs of various industries will be crucial for its success.

Even though the proposed supports have been evaluated in multiple contexts, the systematic framework for early-stage PSS design for sustainability has been evaluated as a whole in a single Danish capital goods manufacturing company, i.e., the primary case company. While the framework exhibits promise, it may face challenges in broader applicability, especially beyond capital goods manufacturing companies. Industries with complex supply chains, such as the electronics or fast-fashion sectors, might encounter difficulties in fully embracing the framework due to the intricacies involved in their design processes. A consequence of this is limited generalisability, in relation to different business types (B2C vs. B2B), various industries, and geographic locations.

The GPM and the consolidated instantiation guidelines have been successfully utilised in three B2B companies, where the complexity of the PSS design is considered higher than in B2C (Mourtzis *et al.*, 2020), thereby indicating that they might be applied in other business types, allowing further testing. Even though the theoretical foundation of the methods lays on numerous cross-sectorial approaches as input, the supports proposed in this research were applied in capital goods manufacturing companies operating in food processing, medical, and HVAC industries, which limits the feedback received to three industries and hinder the inclusion of further industry-specific considerations that might have emerged via application in other (capital goods) manufacturing companies. Further, the empirical studies were conducted in, albeit international and multi-national companies, only Danish manufacturing companies, otherwise known for high awareness and proactive approach towards sustainability issues (Kravchenko, 2020).

A further limitation is related to the staticity of the proposed support. PSS design, especially in the early stages, is known for its dynamicity, i.e., constantly changing and evolving requirements and priorities which impact the design process (Lee *et al.*, 2012). The proposed support, in its current form, advocates an iterative approach with feedback loops both between the content and temporal dimensions but does not allow for automatic adaptation.

Upon the complete utilisation of the framework, a practitioner will end up with a thoroughly developed PSS concept with as high as possible TBL sustainability potential. However, at that point, and given the time restriction of this thesis, only TBL sustainability potential is measurable as opposed to the actual TBL sustainability the PSS concept will have when implemented as a PSS offering in the market. Therefore, a longitudinal study is necessary to fully evaluate the implemented PSS concepts in practice.

4.5 Future research

Several opportunities for future research were identified during this research, both in terms of further improvement and extension of the results of this PhD thesis.

Based on the above-mentioned limitations, this research could be improved and confirmed by:

- further evaluating the framework in its totality, and in different contexts than capital goods companies, where the various contexts should include manufacturing companies of different sizes, industries, business types, PSS readiness, and in different geographical regions to ensure true generalisability;

- converting the framework into a dynamic version that can more closely follow the actual evolvement of the process in use. By incorporating a dynamic perspective, the framework would be better equipped to accommodate real-world complexities and iterations, resulting in more relevant and practical outcomes;
- employing longitudinal case studies to measure the actual TBL sustainability impact of the devised PSS concepts, rather than solely their potential. Such an approach would go beyond mere potential assessment and would provide concrete evidence of the framework's sustainability impact in real-world scenarios.

Based on the other research areas identified as relevant in the academic literature or through empirical research, this research could be extended by:

- expanding the GPM to include embodiment, detailed, and perhaps even front-end innovation phases in an all-encompassing framework. By doing so, the GPM would evolve into an even more comprehensive process that covers the entire PSS design process;
- expanding the GPM to include another layer focused on the communication flows between the actor networks in PSS design. This is considered to enhance collaboration and streamline the decision-making process;
- expanding the BESST to include interactions between the dice and trade-off navigation between different kinds of costs and benefits in the cube. Such enhancements would enable a more nuanced understanding of impacts and benefits, and consequently better decision-making;
- integrating complementary digitalisation insights relevant for nowadays more prevailing smart PSS design (Machchhar *et al.*, 2022). This could significantly improve the framework's practicality and extent of the design space it could support, as smart and data-driven PSS is often seen as a higher level of PSS requiring a solid foundation to be built on;
- focusing on the rapid creation of business cases for PSS concepts, which was identified as of pivotal importance to industry through the case studies with capital goods manufacturing companies. Timely business case development is crucial to gaining industry acceptance and driving the successful adoption of sustainability-motivated PSS solutions;
- expanding the framework to address any type of sustainable business design or the design of socio-technical systems. Further generalisation might help tackle a wider range of sustainability challenges;
- exploring the PSS design in relation to the Science-Based Targets initiative (SBTi), especially scope 3 and 4 emissions, as the initiative is considered to be one of the key instruments to report on the success of PSS solutions in the market;
- expanding the framework with more detailed circularity, sufficiency, and absolute sustainability considerations, as the framework does not guarantee the achievement of any of these concepts due to understudied rebound effects.

5 Conclusion

This chapter consolidates the results of this PhD thesis with respect to the major gap, overall hypothesis and objective, both in terms of knowledge and practice contributions (Section 5.1) and closes off with the final remarks (Section 5.2).

5.1 Research contributions

This PhD thesis was motivated by the challenges manufacturing companies encounter on their route to decouple value creation and economic growth from resource consumption through PSS offerings. Four distinct research gaps (A, B, C, and D detailed in Section 1.3) were identified which jointly make up the major gap in PSS design literature: *the lack of a usable and comprehensive generic framework that can support early-stage PSS design for sustainability in capital goods manufacturing companies.*

To address the major gap, three cycles of the DRM were executed paired with several rigorously executed methods including systematic literature review, action research, interviews, surveys, case studies, and expert validation. The methods were utilised in the primary case company and two other equipment manufacturing companies to reach the overall objective of *developing a systematised framework to support managers in early-stage PSS design for sustainability in capital goods manufacturing companies*.

The core contribution of this PhD thesis is reflected through the *systematic framework for early-stage PSS design for sustainability in capital goods manufacturing companies* which consists of four main parts (see Figure 10):

1. An exhaustive and classified list of drivers and barriers for PSS design elicited both in literature and empirically, which serves to steer PSS design in manufacturing companies;
2. A structured generic process model (GPM) for early-stage sustainable PSS design that unified learnings from 96 identified approaches;
3. Consolidated guidelines to support the implementation and instantiation of the GPM in capital goods manufacturing companies along with the empirically identified instantiation challenges; and
4. A comprehensive PSS concept sustainability screening tool (BESST) for manufacturing companies with the accompanying implementation process.

The four connected contributions directly answer the four main research questions (RQ1-4 documented in Section 4.3). Based on the collected evidence through alternating literature and empirical research and the answers to the research questions, the overall hypothesis of this thesis, stating that *the systematisation of a framework for early-stage PSS design for sustainability can provide useful and usable support for the design of PSS concepts in capital goods manufacturing companies aligned with a TBL-oriented strategy*, was considered justified.

The results presented in this PhD thesis contribute to a number of advancements from academic and industrial perspectives, as elaborated in Sections 5.1.1 and 5.1.2, respectively.

5.1.1 Scientific contributions to knowledge

From an academic perspective, this research has contributed to early-stage PSS design in literature by:

- systematising and expanding the knowledge about PSS drivers and barriers in capital goods manufacturing companies;
- compiling a comprehensive overview of the existing PSS design approaches and their characteristics, including their phases, activities, tools, entities to consider, and sustainability considerations;

- systemising decades of multi-disciplinary PSS design research into a holistic and actionable GPM that consists of a meta-model, i.e., the structure of the process model itself and the reference model which provides the necessary domain knowledge;
- enabling the systematic inclusion of sustainability consideration in the process model;
- recording and mapping the actions and challenges capital goods manufacturing companies encounter when implementing and instantiating the GPM;
- systematising the recorded actions and challenges to propose consolidated guidelines for GPM instantiation;
- identifying and analysing relevant approaches for PSS concept sustainability screening;
- eliciting requirements of a capital goods manufacturing company for PSS concept sustainability screening;
- systematising the relevant dimensions necessary for PSS concept sustainability screening into a useful and novel BESST.

5.1.2 Contributions to practice

From a practical industrial perspective, this research has contributed to manufacturing, especially capital goods manufacturing companies in early-stage PSS design. Being partly driven by the underlying conditions in the empirical setting, characterised by close collaboration with the primary case company, this research had unique circumstances to address contemporary relevant industrial challenges in a scientifically rigorous way. The collaboration provided a tremendous opportunity to reinforce knowledge generation and verify hypotheses and findings.

The output of this thesis supports the practitioners, i.e., decision-making managers and designers in capital goods manufacturing companies to:

- steer the direction and align the priorities in PSS design with the TBL-focused corporate strategies;
- access unified and systematised early-stage PSS design knowledge via a single source (GPM);
- instantiate and embed the GPM to their specific contexts in a proven way;
- change the organisational paradigm towards a more service-oriented way of working;
- systematically and repeatedly design PSS concepts for sustainability;
- quickly but exhaustively screen the TBL potential of each PSS concept.

The application of the supports prescribed in this thesis in capital goods manufacturing companies further demonstrated that they could help to:

- increase knowledge about PSS and its importance in decoupling economic growth and value creation from resource consumption;
- inspire new PSS-based business development opportunities;
- strengthen the existing service offering portfolios;
- deal with ambiguities and uncertainties of intangible service innovation and provision;
- organise results and business proposals for dissemination, i.e., internal employee education and communication with customers.

5.2 Final remarks

This PhD thesis has presented the research and a critical view on how capital goods manufacturing companies might approach early-stage PSS design for sustainability with a systematic framework. It is considered that the framework has great potential to introduce a holistic and structured approach in capital goods manufacturing companies that can yield PSS concepts with high sustainability potential, despite all the elaborated intricacies of PSS.

Research has shown that neither PSS framework adoption by capital goods manufacturing companies nor the PSS sustainability are given, therefore, requiring deliberate considerations expounded in this research. Successful implementation of PSS design frameworks and consequently PSS offerings in the market comes with many challenges, which are not limited to the design domain but entail a much broader scope, in a sense, enveloping the evolution of a company as a whole. Therefore, such organisational transformations require strong buy-in at a strategic level of management of a company. Such a commitment is, however, necessary to drive the economy towards an even more service-dominant value perception inherent to the decoupling of economic growth from unsustainable impacts in any of the three dimensions of sustainability, which is the overarching motivation of this research.

The main result of this PhD thesis, i.e., the systematic framework for early-stage PSS design for sustainability, represents a tangible proposal to navigate manufacturing companies towards the decoupling and reduced impact.

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Appendix A – Descriptive findings of the systematic literature review

The following findings can be accessed at: https://doi.org/10.1016/j.spc.2023.01.020 as supplementary material attached to the Appended Publication 2.

1 Descriptive findings

From the selected papers, the most prolific authors are Shimomura, Y. (7), Sakao, T. (6), and Stark, R. (4). With regards to the subject area, the majority of approaches come from authors with an engineering and design background (56.8 %), then from Business and Management (22.9 %), and finally 20.3 % from IT, as defined by (Boehm and Thomas, 2013). The distribution that strongly favours engineering and design is expected, as this is where the notion of conceptual design primarily comes from.

The three largest sources of selected publications (Table A1) are Procedia CIRP (14), Journal of Cleaner Production (10) and Sustainability Switzerland (4). Such a distribution is expected, as CIRP ran a PSS-dedicated conference until 2019, and the sustainable and circular solutions often based on PSS are up-and-coming in the sustainability-focused journals.

Germany leads in the number of publications (19), followed by Sweden (12) and Italy (10). The number of publications per year (2001-2022) greatly varies (Figure A1), with a first steeper rising trend in 2009 as PSS gets some traction in the industry and then in 2015 corresponding to an increase in CE-related research. The maximum number of selected papers (10) was published in 2009 while no relevant publications were found in the years 2002 and 2004.

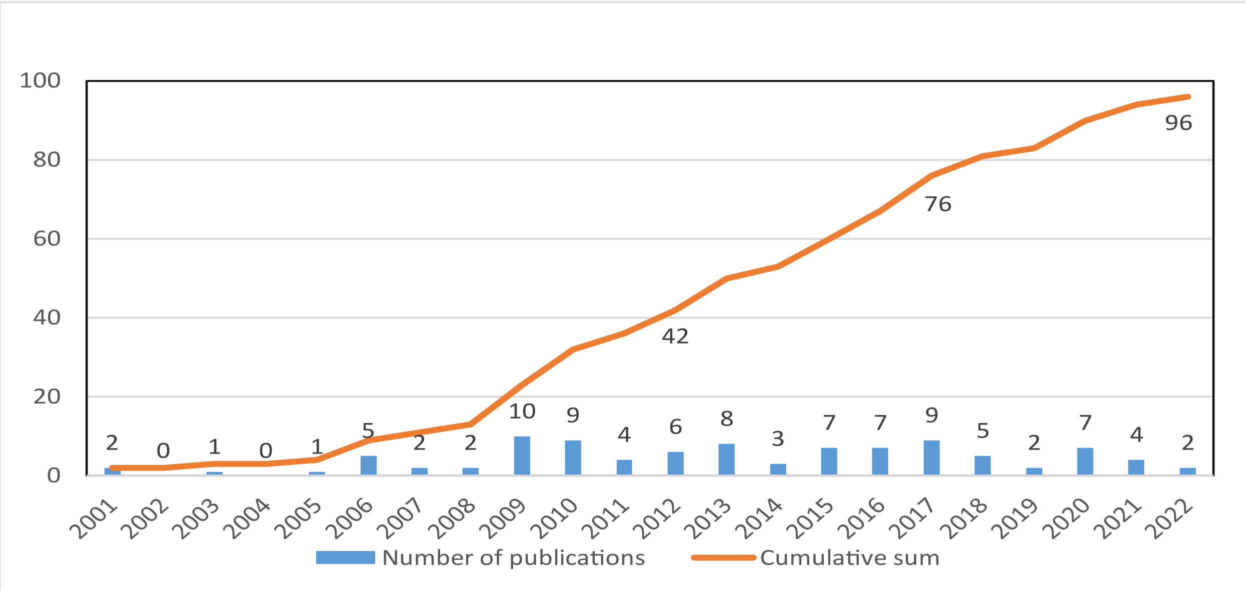

Figure A1. Temporal distribution of the selected publications.

Figure A2 shows the overview of the (a) number of approaches that focus on particular clusters of entities (explained in detail in Section 4.1); (b) the number of papers from different subject areas (as classified by Scopus); and (c) other considerations (TBL, life cycle and CE) that the selected approaches took into account, which can be observed in more detail in Table A1.

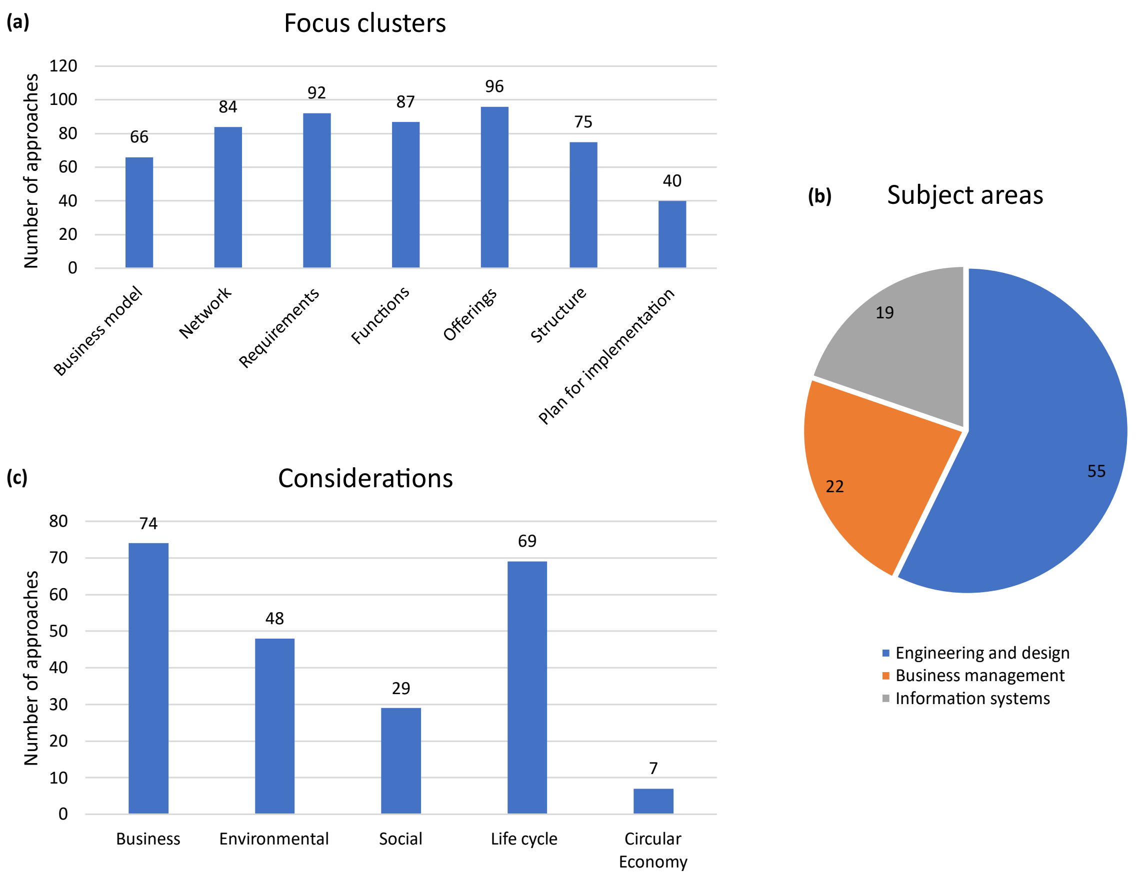

Figure A2. The overview of the selected 96 approaches with respect to (a) cluster entities they focus on, (b) the subject areas they stem from, and (c) the considerations accounted for.

2 Approaches selected for the analysis

Table A1 showcases the selected approaches compared with respect to their background, industrial application, depth, width, and length.

Table A1. The list of selected PSS approaches with a summary of their characteristics. Bolded references account for all the clusters and considerations. Legend for different columns:

- *Focus clusters(s): B – business model, N – actor-network, R – requirements, F – function, O – offerings, S – structure, P – plan. B* - not explicitly mentioning business models but the value in terms of benefits and costs or use scenarios.*
- *Background (as classified by Scopus): BM – business & management, ED – engineering & design, IT – information technology.*
- *The method considers: TBL sustainability (B – business, E – environmental, S – social), CE – circular economy, LC – life cycle.*

No.	Reference	Description	Focus cluster(s)	Back-ground	Conside r-ation
1	(Luiten *et al.*, 2001)	The Kathalys method. Five tracks should be pursued concurrently through five phases to develop SPSS.	N, R, F, O	ED	B, E
2	(Brezet *et al.*, 2001)	Design of eco-efficient services (DES). The six-phase methodology consists of two parts: (i) offering design and (ii) policy formulation and new PSS ideation.	N, R, F, O, S	ED	B, E, LC
3	(Maxwell and Van der Vorst, 2003)	Sustainable product and/or service development (SPSD). The life cycle-oriented TBL method focused on PSS functionality.	N, R, F, O	ED	B, E, S, LC

4	(Van Halen *et al.*, 2005)	Methodology for product-service systems (MEPSS). A comprehensive modular five-phase methodology for sustainable PSS design.	B*, N, R, F, O, S, P	ED	B, E, S, LC
5	(Aurich *et al.*, 2006)	Life cycle-oriented modular process for the systematic design of product-related technical services.	B*, N, R, F, O, S, P	ED	B, E, S, LC
6	(Matzen and Mcaloone, 2006)	A model for conceptualising the development of PSS based on the modelling of service activities.	B, N, R, O	ED	B, LC
7	(Lindahl *et al.*, 2006)	The interactive design method for service engineering of functional sales offers focused on the design for the environment.	N, R, F, O	ED	B, E, LC
8	(Morelli, 2006)	Methodological approach to design PSS to be used as a catalyser of solution-oriented partnerships.	B*, N, R, F, O, S, P	ED	LC
9	(Tukker and Tischner, 2006)	A comprehensive practical guide for PSS development consisting of five steps and supporting tools.	B*, N, R, F, O, S, P	BM	B, E, S, LC
10	(Alonso-Rasgado *et al.*, 2006)	A five-stage design process for rapid creation of Total Care Products which integrates hardware and services into a complete functional provision for customers.	B*, N, R, F, O	ED	B
11	(Sakao and Shimomura, 2007)	Service engineering (SE). The twelve-step generic design process for service and product design is based on flow, scope, view and scenario models, and receiver state parameters (RSP).	B*, N, R, F, O	ED	B, E, LC
12	(Welp and Sadek, 2008)	Extended heterogeneous IPS² concept modelling approach. The early stage of PSS design is structured in four modelling planes (function, object, process, and system behaviour)	R, F, O, S	IT	/
13	(Verbraeck and van de Kar, 2008)	APSIT method. An elaborate five-phase method focusing on the service concept, technological architecture, and the organisational network.	B*, N, R, F, O, S, P	BM	B, LC
14	(Uchihira *et al.*, 2008)	DFACE-SI methodology. A five-step design process to establish a common vision of a product-based service business among the stakeholders.	B, N, R, F, O, S, P	IT	B
15	(Pawar *et al.*, 2009)	The PSO triangle. A PSS development process which simultaneously considers product, service and organisation design for value creation.	B, N, R, F, O, S	BM	B, E, LC
16	(Rexfelt and Hiort Af Ornäs, 2009)	A methodology for conceptual development of PSS adapted from user-centred design.	B*, N, R, F, O,	BM	B, E, S

17	(Kimita *et al.*, 2009)	An estimation method of customer satisfaction for PSS design solutions in the conceptual design stage.	B*, N, R, F, O, P	BM	B, E, S
18	(Komoto and Tomiyama, 2009)	A systematic modelling method for the generation of PSS design concepts facilitated by a CAD tool.	B, N, R, F, O	ED	B, LC
19	(Huertas-García and Consolación-Segura, 2009)	A six-step methodology to design product and service concept alternatives design based on statistical design of experiments and quality function deployment.	B*, N, R, F, O	BM	/
20	(Maussang *et al.*, 2009)	A PSS design methodology based on function-oriented scenarios and focused on engineering product criteria.	N, R, F, O, S, P	ED	B, E, S, LC
21	(Shimomura *et al.*, 2009)	A method for concurrent and collaborative design of PSS based on a unified representation scheme.	N, F, O, S	ED	/
22	(Sakao *et al.*, 2009)	A seven-step structured method for PSS design that addresses customer value through extended quality function deployment.	N, R, F, O, S	IT	B
23	(Müller *et al.*, 2009)	PSS Layer Method. A method to synthesise PSS ideas and concepts.	B, N, R, F, O, S, P	ED	B, E, S, LC
24	(Baxter *et al.*, 2009)	A framework for knowledge reuse in PSS design based on three models: process-based design model, manufacturing capability knowledge and service knowledge.	B, R, F, O, S, P	IT	B, LC
25	(Geng *et al.*, 2010)	A three-domain (customer, functional and product-service) framework for conceptual design of PSS based on quality function deployment.	N, R, F, O	IT	LC
26	(Becker *et al.*, 2010)	A conceptual framework for integrated design of value bundles for PSS.	B, N, R, F, O, S	IT	B, E, LC
27	(Kim, Lee, *et al.*, 2010)	A six-step systematic methodology for the design process of PSS based on activities and functions.	B*, N, R, F, O, S	ED	B, LC
28	(Sadek and Theiss, 2010)	IPS² concept development methodology assisted by different knowledge domains.	B*, N, R, F, O, S	IT	B
29	(Müller and Stark, 2010)	A generic PSS and IPS² development process model based on the extended V-model from product development.	B, N, R, F, O, S, P	ED	B, LC
30	(Zhang and Chu, 2010)	An approach that supports the conceptual design of product and maintenance (P&M) based on quality function deployment and failure mode analysis.	R, F, O, S	IT	B, LC

31	(Alix and Vallespir, 2010)	A framework for new product-service development for manufacturing firms organised in four sequences.	B*, N, R, F, O, S, P	IT	B
32	(Kim, Lim, *et al.*, 2010)	A PSS concept generation support system. The methodology is based on the analysis of existing PSS cases.	B, N, R, F, O, S	ED	B, E, S, LC
33	(Lee and Kim, 2010)	A PSS design framework which utilises functional modelling and service activities, which are mapped to product and service elements to yield PSS concepts.	N, F, O, S	ED	/
34	(Kim *et al.*, 2011)	A six-phase PSS design process supported by several PSS design tools (e.g., DesignScape, Life-Cycle Step, E3 Value).	B*, N, R, F, O, S	ED	LC
35	(Vasantha *et al.*, 2011)	A PSS conceptual design framework founded on stakeholders' co-creation, responsibility, and competence.	B, N, R, F, O, S, P	ED	B, E, S, LC
36	(Geng and Chu, 2011)	PSS conceptual design approach consisting of three user task, function, and conceptual service blueprint models.	N, R, F, O	ED	/
37	(Lee and Abuali, 2011)	Innovative Product Advanced Service Systems (I-PASS) methodology. A five-step systemic thinking methodology for dominant PSS concept design.	B, N, R, F, O, S	ED	B, LC
38	(Kim and Yoon, 2012)	An approach based on the theory of inventive problem solving (TRIZ) and QFD to create PSS concepts by resolving contradictions between product and service components.	B, N, R, F, O, S, P	BM	B, E
39	(Hussain *et al.*, 2012)	A 10-step capability-based framework that utilises system-in-use (rather than just product-in-use) data to inform conceptual PSS design.	B, N, R, F, O, S	IT	B
40	(Akasaka *et al.*, 2012)	Method to support PSS conceptual design, and particularly the PSS idea generation through knowledge obtained from multiple PSS cases.	N, R, F, O, S	ED	B, E, LC
41	(Mougaard *et al.*, 2012)	PSS conceptualisation framework focused on the actor network.	B*, N, O	ED	LC
42	(Lindström *et al.*, 2012)	A conceptual development process for functional products and their management in operation.	B, N, R, F, O, S, P	BM	B, LC
43	(Lim *et al.*, 2012)	PSS Board. A structured visualisation for the design of PSS processes based on the Universal Job Map.	N, R F, O, S, P	ED	B, E
44	(Bertoni *et al.*, 2013)	A visual Lifecycle Value Representation Approach (LiVReA) for preliminary stages of PSS design.	B*, N, R, F, O, S	ED	B, LC
45	(Ny *et al.*, 2013)	A strategic approach for sustainable PSS development based on established sustainable product development tools.	B, N, R, F, O, S	ED	B, E, S, LC

46	(Yang and Xing, 2013)	An approach for innovative PSS concept generation based on TRIZ adjusted to PSS design.	R, F, O	ED	E, LC
47	(Herzberger *et al.*, 2013)	An interactive modelling procedure for PSS concepts based on the business model canvas, PSS life cycle and PSS configurator.	B, N, R, F O, S, P	BM	B, LC
48	(Yang *et al.*, 2013)	A seven-step integral process for the conceptual design of PSS focused on the identification of servicing modes.	R, F, O	ED	LC
49	(Zhang, 2013)	A performance-oriented conceptual design framework for PSS. Includes three domains: requirement domain, performance domain, and concept domain.	R, F, O, S	ED	/
50	(Marques *et al.*, 2013)	A four-step methodology for PSS development that promotes parallel execution of product and service design activities.	B, N, R, F, O, S, P	ED	B, LC
51	(Carreira *et al.*, 2013)	An extended Kansei engineering method that incorporates experience requirements and collaboration in PSS design.	N, R, F, O, S	ED	S
52	(Chen *et al.*, 2014)	A conceptual design framework based on the Axiom Design approach which consists of the customer domain, function domain and concept domain.	N, R, F, O, S	BM	LC
53	(Meuris *et al.*, 2014)	The conceptual design phase of IPS² based on the comparison with an industrial use case.	B, N, R, F, O, S, P	ED	B, LC
54	(Nguyen *et al.*, 2014)	A method for operationalizing the IPS² development process through concrete project plans.	B, N, R, O, S, P	ED	B, LC
55	(Vezzoli *et al.*, 2014)	SPSS development process consisting of five activity clusters and three phases which results in a PSS concept. Based on the actor network, experimentation, and learning.	B, N, R, F, O, S, P	BM	B, E, S, LC
56	(Park and Yoon, 2015)	A four-step approach to identifying PSS concepts through a combination of web news mining and chance discovery theory.	B, N, R, F, O, S	IT	B, E
57	(Nemoto *et al.*, 2015)	A framework for managing and utilising PSS design knowledge in the conceptual design stage of PSS.	N, R, F, O, S	IT	B, E, S, LC
58	(Sutanto *et al.*, 2015)	A three-stage methodology founded on the integration of product and service requirements for the design of PSS concepts.	R, F, O, S	ED	B, E, S
59	(Schmidt *et al.*, 2015)	An early-stage PSS planning and decision-making process model which allows for	B*, R, O, S, P	ED	/

		higher customer integration and adaptable requirements.			
60	(Pezzotta *et al.*, 2015)	A Service Engineering framework that integrates Service CAD methodology and discrete event simulation.	B*, N, R, F, O, S, P	IT	B, E, LC
61	(Barquet *et al.*, 2015)	A guideline to support the design of PSS business models focused on the fuzzy front-end.	B, N, O, S	BM	B
62	(Moser *et al.*, 2015)	A generic five-step PSS development process with methods that support every phase.	N, R, O, S, P	ED	LC
63	(Pigosso and McAloone, 2016)	An approach for the environmentally sustainable PSS design based on the seven-phase ecodesign maturity model (EcoM2) and 30 best practices for PSS development	B, N, R, F, O, S, P	ED	B, E, LC
64	(Rondini *et al.*, 2016)	Product-Service Concept Tree (PSCT). A method that proposes a way to identify, represent and select PSS concepts for implementation.	B, N, R, F, O, S	ED	LC
65	(Yang *et al.*, 2016)	A multi-route process for innovative PSS concept generation based on TRIZ and capable of solving contradictions of different natures.	R, F, O, S, P	ED	B, LC
66	(Park *et al.*, 2016)	An approach to generate new PSS concepts by employing general needs fulfilled by existing PSS and business system evolution patterns.	B*, R, F, O, S	BM	B, E, LC
67	(Rosa *et al.*, 2016)	A design thinking-based PSS concept definition process adapted from Bootcamp Bootleg (Doorley *et al.*, 2018) methodology.	B, N, R, F, O	ED	B
68	(Trevisan and Brissaud, 2016)	A ‘‘multi-views’’ modelling framework for supporting integrated PSS design based on three models: result, structure, and structural organisation.	N, R, F, O, S, P	ED	LC
69	(Zine *et al.*, 2016)	A generic approach for customer-participative PSS design process for the machine tool industry.	B, N, R, F, O, S, P	IT	B, LC
70	(Song and Sakao, 2017)	A module-based framework for the early-stage design of sustainable PSS oriented on customisation.	N, R, F, O, S	ED	B, E, LC
71	(Sousa-Zomer and Miguel, 2017)	A QFD-based approach for PSS conceptual design which translates stakeholders' requirements into three sustainability dimensions.	N, R, F, O, S	ED	B, E, S, LC
72	(Adrodegari *et al.*, 2017)	A two-level hierarchical framework for PSS business model design based on an expanded business model canvas.	B, N, R, F, O, S, P	BM	B, LC

73	(Haber and Fargnoli, 2017b)	Functional Engineered Product-Service System (FEPSS). A four-phase generic PSS conceptualisation methodology based on morphological thinking.	B, N, R, F, O, P	BM	B, E, LC
74	(Boukhris *et al.*, 2017)	COSUP method for co-creation with stakeholders in early PSS concept generation.	B*, N, R, F, O, S	ED	/
75	(Idrissi *et al.*, 2017)	A generic modelling meta-model (nine types of models) that supports an integrated PSS design process.	B, N, R, F, O, S, P	ED	LC
76	(Haber and Fargnoli, 2017a)	A four-stage unified approach derived from design science and built on the differences between the existing methods identified in the literature.	B, N, R, F, O, S, P	BM	B, E, LC
77	(Pezzotta *et al.*, 2018)	Product Service System Lean Design Methodology (PSSLDM). A four-phase methodology based on Service Engineering and extended by lean rules for full lifecycle PSS development.	N, R, O, S, P	BM	B, E, LC
78	(Chen, 2018)	A four-step approach for developing sustainable PSS in the early design phases.	B, N, R, F, O, S	BM	B, E, S, LC, CE
79	(Chiu *et al.*, 2018)	An integrated PSS modelling process with a TBL focus that enables the development of many alternative PSS scenarios.	B, N, R, O, S	BM	B, E, S, LC
80	(Andriankaja *et al.*, 2018)	A four-phase PSS design method based on functional analysis and characterised by a high level of integration, industrial applicability, and balance of stakeholders' value.	B, N, R, F, O, S, P	ED	B, LC
81	(Khan and Wuest, 2018)	A four-phase conceptual design framework for upgradable PSS focused on the beginning of life.	B, N, R, F, O	ED	B, E, S, LC, CE
82	(Pieroni *et al.*, 2019b)	A configurator for the design and assessment of customer value, economic growth and resource decoupling potential for product-service system business models in practice.	B, N, R, F, O, S, P	BM	B, E, S, LC, CE
83	(Bertoni and Bertoni, 2019)	A five-step systematic framework for modelling and assessing "ilities" in early PSS design.	B, N, R, F, O, S	ED	B, LC
84	(Neramballi *et al.*, 2020)	A design navigator for lifecycle-oriented function deployment (LDF) to support the conceptual redesign of existing industrial offerings towards PSS.	B, R, F, O, S	ED	B, E, LC, CE
85	(Wall *et al.*, 2020)	Model-Driven Decision Arena (MDDA). An environment for collaborative decision-making that focuses on the early design phases of PSS.	B, N, R, F, O, S	IT	B, E, S, LC

86	(Peruzzini and Wiesner, 2020)	A seven-phase systematic, transdisciplinary, and collaborative framework for the PSS design process.	B, N, R, F, O, S, P	ED	B, E, S, LC
87	(Bal and Satoglu, 2020)	An Axiomatic Design Framework for SPSS where conceptual design is based on the TBL.	B, R, F, O	IT	B, E, S, LC, CE
88	(Sakao and Neramballi, 2020)	A consolidated schema consisting of 10 design steps for PSS conceptual design.	B, N, R, F, O, S, P	IT	B, E, LC, CE
89	(Doualle *et al.*, 2020)	A decision support method for the design and selection of SPSS scenarios during early design stages.	B*, N, R, F, O	ED	B, E, S, LC
90	(Barravecchia *et al.*, 2020)	The player-interface (PI) method. A three-phase approach to support PS concept generation based on the interactions between PSS players.	N, R, F, O, S	ED	LC
91	(Rosa *et al.*, 2021)	A concept map that can serve as a checklist (does not recommend a phase-like process) to support the planning and evaluation of artefacts in the initial phases of PSS design.	B, N, R, F, O, S, P	ED	B, E, S, LC
92	(Sakwe *et al.*, 2021)	An FMEA-based method to support prioritisation of critical failures in performance PSS development.	B, N, R, F, O.	IT	/
93	(Wu *et al.*, 2021)	A function-oriented optimising approach for the conceptual design of smart PSS based on the five-dimensional digital twin model.	N, R, F, O, S	IT	B, E
94	(Zhang *et al.*, 2021)	A five-stage framework for early-stage SPSS development based on design-centric complexity (DCC) theory	N, R, F, O, S	ED	B, E, S, LC
95	(Kolling *et al.*, 2022)	A conceptual model for implementing product-oriented PSS in the agricultural machinery sector.	B, N, R, O, S	BM	B, E, S, LC, CE
96	(Moro *et al.*, 2022)	A PSS Business Model Framework Towards Sustainable Production and Consumption.	B, N, R, F, O, S	BM	B, E, S, LC

3 IDEF0 in the PSS development arena

3.1 Inputs and outputs

(Aurich *et al.*, 2006) suggested that input and output identification in the PSS design process represents a major challenge and need in future research, but even today, there is a surprising disparity between the inputs and output of activities in different process models discovered by the authors, and a clear link is often missing between the output of one phase and the input of the next phase. Among the existing approaches, few methodologies identify inputs and outputs at the activity level (e.g., (Van Halen *et al.*, 2005)), while the majority of the approaches describe the inputs and outputs at a high level of phases (Clayton *et al.*, 2012).

Song and Sakao (2017) utilised the input-output logic to establish a PSS customisation framework in which outputs from one phase serve as inputs to one or more of the following phases.

The inputs and outputs of the activities and phases usually refer to data or information obtained either from previous design activities or collected from various elements of the system-in-use, and since the value-in-use only manifests at the point of consumption, the system-in-use, i.e., the use context has to be considered to acquire the needed inputs (Hussain *et al.*, 2012).

3.2 Mechanisms and constraints

It is well documented that the transition towards PSS can yield the expected optimal returns only if supported by established mechanisms and tools (Rondini *et al.*, 2016). Therefore, this review also encompasses the identification of tools for the facilitation of designing the constituent entities throughout the process, as can also be seen in the supplementary material. For example, the Quality Function Deployment (QFD) is considered a useful tool for requirements definition (Sousa-Zomer and Miguel, 2017), while the function deployment diagram (FDD) offers great support in analysing and defining the function entity (Maussang *et al.*, 2009).

The authors furthermore identified constraints for activity execution in terms of the institutional framework dimension consisting of regulatory, normative, and cognitive constraints which include policy instruments such as environmental taxes, values and norms in society and individuals' interpretations of reality (Mont, 2004b).

Appended Publications

The appended publications that support the argumentation of this PhD thesis and present the detailed results are appended in the following pages are presented. An EDGE INDEX is available to help locating each of the five publications.

The publications as are appended in the following order:

Publication 1 (Conference paper) – Drivers and barriers in practice

Sarancic, D., Pigosso, D.C.A., and McAloone, T.C. (2021), "Sustainability driven Product-Service Systems development: a case study in a capital goods manufacturing company", *KES-SDM 2021 Conference*, Vol. 262 SIST, Springer Singapore, pp. 1–11. Doi:10.1007/978-981-16-6128-0_1.

Publication 2 (Journal paper) – Development of the Generic Process Model (GPM)

Sarancic, D., Pigosso, D.C.A., Pezzotta, G., Pirola, F. and McAloone, T.C. (2023), "Designing sustainable product-service systems: A generic process model for the early stages", Sustainable Production and Consumption, Elsevier, Vol. 36, pp. 397–414. Doi:10.1016/j.spc.2023.01.020.

Publication 3 (Journal paper) – Evaluation and Instantiation of the Generic Process Model (GPM)

Sarancic, D., Pigosso, D.C.A., and McAloone, T.C. (2023), "Evaluation and instantiation of a generic process model for early-stage sustainable Product-Service System (PSS) design within three manufacturing companies", *(Manuscript under review at the Journal of Cleaner Production).*

Publication 4 (Journal Paper) – Development of the Business, Environmental and Social Screening Tool for Product-Service Systems (BESST).

Sarancic, D., Pigosso, D.C.A., Colli, M., and McAloone, T.C. (2022), "Towards a novel Business, Environmental and Social Screening Tool for Product-Service Systems (BESST PSS) design", *Sustainable Production and Consumption*, Elsevier, Vol. 33, pp. 454–465. Doi:10.1016/j.spc.2022.07.022.

Publication 5 (Conference paper) – BESST case study

Sarancic, D., Metic, J., Pigosso, D.C.A. and McAloone, T.C. (2023), "Impacts, synergies, and rebound effects arising in combinations of Product-Service Systems (PSS) and circularity strategies", Procedia CIRP, Vol. 116, pp. 546–551. Doi.org/10.1016/j.procir.2023.02.092.

Appended Publication 1

Sarancic, D., Pigosso, D.C.A., and McAloone, T.C. (2021), “Sustainability driven Product-Service Systems development: a case study in a capital goods manufacturing company”, KES-SDM 2021 Conference, Vol. 262 SIST, Springer Singapore, pp. 1–11. doi:10.1007/978-981-16-6128-0_1.

Sustainability Driven Product-Service Systems Development: A Case Study in a Capital Goods Manufacturing Company

David Sarancic(✉), Daniela C. A. Pigosso, and Tim C. McAloone

Technical University of Denmark, 2800 Kongens Lyngby, Denmark
dasar@mek.dtu.dk

Abstract. This paper aims to present early considerations in the process of Product-Service System (PSS) development driven by sustainability in a capital goods manufacturing company. Based on the elicitation of drivers and barriers for such companies to introduce PSS, the empirical study described in the paper reports on the experiences from representative professionals within the case company gained through a series of interviews. The conducted investigation reveals that whilst displaying some basic similarities, the focus of PSS development in capital goods manufacturing companies is characteristically different than in other manufacturers. Key differences include that capital goods manufacturers ought to: see co-creation of the offering with the customer as being of crucial importance (to ensure efficiency and effectiveness); place a stronger focus on the use phase of their products and related services (to extend the useful life of the product); and be granted ready access to customers' products and their use data (in order to pro-vide through-life services). Differences have also been observed in the way that different parts of the manufacturing organization perceive drivers and barriers for the introduction of PSS.

Keywords: Product-Service Systems (PSS) · Capital goods manufacturer · Drivers · Barriers

1 Introduction

Driven by the earning opportunities on one side and environmental responsibility on the other, manufacturing firms are looking into alternative business models capable of capitalizing on both [1]. Business models within the Circular Economy (CE) paradigm have the potential to address the needs of manufacturing firms by a different, circular means of value creation [2]. The goal of such a paradigm is to reach mutually reinforcing business and sustainability drivers [3], thus decoupling value and wealth creation from resource consumption. Product-Service System (PSS), although not necessarily sustainable or circular [4], is one of the most promising ways of realizing the CE goal of decoupling economic success from material consumption, by means of proactively building in new forms of value creation that either more effectively utilize the material goods, or supplement them, through activity- and knowledge-based offerings [5].

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Despite the wealth of literature addressing PSS design [6], there is a lack of knowledge about the exact offering development process that a manufacturing company is to adopt and conduct to systematically and repeatedly introduce PSS offerings. The knowledge gap widens further when focusing on a specific kind of manufacturing companies that produce capital goods [7], where PSS encounters distinct barriers related to a large number of installed products with long life cycles.

Manufacturing companies currently secure a significant part of their revenue through point-of-sales of physical products [7]. There is, however, an increasing trend among capital goods manufacturers to acquire more significant shares of revenue from through-life services, capitalizing on the already installed base of products, both from the business and sustainability perspectives [8]. A service-based model could extend product life and reduce the manufacture of new products, hence decreasing the environmental impact [5]. Lack of knowledge, resources and customers insights are just some of the many challenges to overcome in the process of PSS development. Focusing on a capital goods manufacturing company, this paper charts and compares literature and empirical findings, regarding the drivers and barriers for the introduction of PSS, with an aim to support the process of PSS development.

2 Methodology

Research Questions. This paper aims to showcase real-world drivers and barriers in the early development process of PSS within a capital goods manufacturing company. Hence, the following research questions were formulated:

1. What are the internally perceived drivers and barriers for the introduction of PSS and how do they compare to literature findings?
2. How do the different parts of the capital goods manufacturing organization perceive drivers and barriers for the introduction of PSS?

Data Collection and Analysis. The principal data for this paper was retrieved through the empirical study based on semi-structured exploratory interviews in a single case company. The single case study is considered an appropriate approach as it allows for a thorough research enquiry and it provides a new lens on important exceptions that question the *status quo* [9]. The empirical study is supported by a previously conducted literature review by the authors on drivers and barriers in capital goods manufacturing companies to introduce PSS [10].

The interviews followed a conventional sequence according to Robson and McCartan [11]. Before the interviews, all interviewees were introduced to the field of PSS through a video presentation, prepared by the author. The purpose of the "video pre-read" was to introduce the interviewees to the terminology, provide sufficient time to reflect on the topic and relate the topic of PSS to their own experiences within the company. The interviews were designed around two main questions:

1. What motives does the company have to introduce PSS?
2. What challenges can you think of to introduce PSS?

In total, 18 interviewees covering diverse functions (R&D, sales, field engineering, etc.) and seniority levels (CxO, team lead, manager) were selected to participate in the interviews. Any function that has a relation to the service provision was aimed to be included to paint a comprehensive picture of perceptions throughout the company. The interviews were recorded and transcribed, resulting in more than 150 pages of interview data. Data were analyzed through inductive research analysis and the analytical reflection of the data was done by the emergent identification of patterns [12].

Case Company. The empirical context for this research is a capital goods manufacturing company. The company is in the business of producing machinery and equipment for the food and beverage industry. At the time of writing, the company is in the early stages of the development and introduction of PSS for its business. The company has the ambition to adopt PSS as a means of increasing its competitiveness on the market that could potentially also contribute to its sustainability strategy.

3 Empirical Insights

Drivers and barriers as elicited from the interviewees were classified into three categories: (i) strategic, (ii), tactical and (iii) operational, corresponding to different levels of the organization. The strategic category encompasses long-term objectives, relations, and value creation. The tactical drivers and barriers are oriented towards more specific goals and performance indicators, while the operational level includes individual actions. These categories also correspond to different seniority levels of the interviewees, where executives are classified as a strategic position, mid-managers as tactical positions, and operational position implies functions in the manufacturing facility or similar. Responses were classified axiomatically in the three categories, with respect to the temporal and executional horizon that the respondents felt each driver and barrier to be.

Through the interviews and literature review, a total of 37 drivers and 45 barriers were elicited for the introduction of PSS. Nineteen drivers were classified as strategic, 13 as tactical and 5 as operational. Complementing the findings from the literature, 8 new drivers and 5 new barriers were revealed. Some of these were not present in the literature, while some had a noticeably altered perspective than in the literature, seen from the perspective of the capital goods manufacturing company. This discrepancy in the number of identified drivers and barriers in the literature highlights the relevance of combining literature studies with empirical studies, especially when applying to new and more specific contexts, such as the capital goods sector.

Interesting trends can be observed in Fig. 1, showing the relation of drivers and barriers in each of the three categories. It is evident that barriers tend to be more tactical and operational than strategic, on the other hand, drivers tend to be more strategic. This incongruity is of special importance in the early phase of PSS development, or even in the company's strategy development. It is relatively straightforward to see the benefits that PSS might bring on a strategic level, and not so many barriers are perceived to adopt it as a strategic goal, however, as the high-level goals become more operational, many barriers appear that deflate the expectations. Therefore, an in-depth study like this might

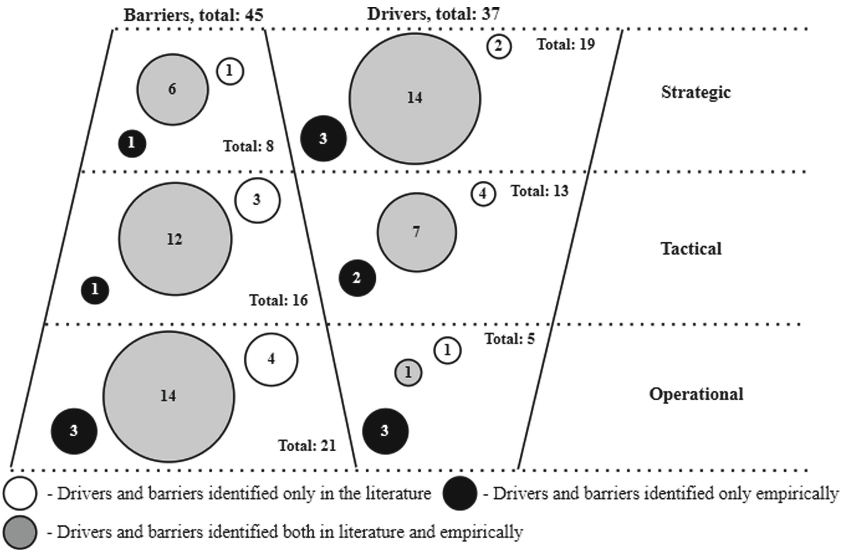

Fig. 1. Classification of drivers and barriers for PSS development elicited empirically and through literature review in three different categories: strategic, tactical, and operational.

bridge the classic mismatch between strategic and operational levels and make the PSS development process and expectations more transparent.

The following sections elaborate on unveiled drivers and barriers for PSS development in a capital goods manufacturing company. This overview is focused on the drivers and barriers that were brought forward most often by the interviewees.

Drivers. *Strategic.* The overarching strategic driver for the case company to introduce PSS is sustainability. This driver is organized according to the triple bottom line, tackling environmental, social and economic dimensions, respectively. These dimensions more specifically mean that PSS is driven by the desire for stronger and long-lasting partnerships, reduced environmental impact and increased and stabilized revenue over time, which are all already recognized drivers [8, 13]. One of the interviewees said: "*CO_2 emission reduction is our biggest strategic target.*", while another said: "*We need to be less dependent on individual transactions and build recurring income streams.*"

Many interviewees pointed out the importance of customer involvement in the development process of PSS, but also the interaction with the customers and products throughout the products' lifetime. A comment from one of the senior managers was: "*Introduction of services will bring product development closer to customers",* while another said: *"…if we get deep insight into the performance of our products, we could get insight into the behaviour of our customers and that is a key differentiator from most of the competition."*. Some of the authors mention customer involvement and knowledge sharing as drivers [6], however, most of them focus on the pre-use involvement, while the use phase of capital goods seems to be of greater impact in the B2B context, both in financial and environmental terms [14]. Strategic differentiation among the competition is one of the most mentioned drivers for the introduction of PSS [15].

Drivers recognized by the interviewees are the adoption of the culture around value in use and the total cost of ownership (TCO) for the installed base of products. One of the senior managers stressed that: "*there is an abundance of opportunities to provide more value through services along with the products' lifetime [...] even more so if the services extend the lifetime*". Baines et al. [5] talk about the potential to decouple environmental pressure from economic growth by focusing on asset use, however, it is argued that the potential environmental benefit may be evaluated only after deep knowledge about customers and products is obtained.

The interviewees, alike some authors, recognized the connection that sustainability, digitalization and servitisation have [16]. Those are perceived as mutually reinforcing concepts for a future-proof business: *"data collection on services and customer use today will enable big data and artificial intelligence solutions in the future"*.

Tactical. The second category of drivers concerns more tangible motives to introduce PSS in a capital good manufacturing company. The reasons to introduce PSS as stated by some of the interviewees are: *"to increase overall equipment effectiveness (OEE) and through services increase availability, performance and quality"* and *"to reduce lost time in changeovers, maintenance, cleaning and start-ups"*. Some authors argue that product efficiency can be increased by PSS on a high level [17], however, these empirical findings dig much deeper into the problematic area.

There are other benefits of PSS as recognized by an interviewee who said: *"Services could contribute to a reduction of waste, energy and water used in production."*, which are the most environmentally impactful actions for an in-use asset. That statement is supported by Kjaer et al. [4], who see PSS as an enabler of resource reduction.

Another tactical driver is to enable the supply of better quality products by feeding back the information obtained through the service interactions with customers, as recognized by Mont [13]. In this way, "*partnerships can be built with suppliers beneficial to all parties",* as stated by an interviewee.

Structure in dealing with service callouts has been recognized by an interviewee who said: *"We should reduce firefighting at customers and have a standard way to deal with it"*. This observation goes in hand with that of another interviewee who said: *"…through services we could learn much more about our warranty cases and win them more often",* which can be tied back to knowing the products' performance and customers' behaviour. Communication with customers about end-of-life product condition was also noted as a driver as it is perceived that many services could be revolved around the provision of circular activities such as upgrade, refurbishment, resale, and recycling.

Operational. Only a couple of operational drivers were elicited for the introduction of PSS through empirical research. Those refer to learning more about wear and critical parts and internal training and procedures for routine service operations such as maintenance and cleaning of products. Finally, one of the interviewees said: *"…if we were our customers, we would not make a product that is difficult or expensive to operate.",* implying that service capabilities that would enable ease and affordability of operation have to first be developed internally before being able to teach customers the same.

Barriers. *Strategic.* The first strategic barrier is closely related to the first strategic driver, a knowledge barrier to the connection between sustainability and services. This difficulty to clearly define offerings, set unambiguous performance indicators and trace the transition is a barrier recognized by numerous authors [12]. One of the interviewees said: *"We do not have a common understanding of sustainability, let alone how services influence it."*. Evaluation of service potential has been also raised by the commentators in previous studies [17, 18]. Another strategic barrier concerns the framing of the offerings for various customer segments and their respective business strategies. One of the interview claims is: *"We have very limited knowledge of our customers' strategies and views on receiving services from us",* a barrier also noted by Adrodegari et al. [7].

A further barrier is the ability to amortize extended payment periods that come with PSS and the viability of investing in the development of PSS offerings rather than other projects. Several interviewees claim that: *"…it is challenging to estimate the financial potential of PSS solutions.",* which is also stressed by numerous authors [3, 18].

Tactical. While the literature recognizes barriers such as the difficulty to fully understand customers' needs [18] and the inaccuracy of predicting customers' usage [17], the findings of this empirical study enunciate these barriers as crucial to the success of the service-related business. Several interviewees stated that the company has very limited knowledge of what service needs do their customers have. An interviewee said: *"We need to observe customers and talk to them more."*. A recurring theme in the interviews was also the lack of knowledge of how exactly customers use the company's products. An interview said: *"We think customers use our products in a certain way, but we don't know with certainty, meaning that we do not know the products' exact performance*". Therefore, it seems that such insights would greatly help in streamlining the capital goods with long lifetimes for ease of use and consequently bring more value. There is potential to capitalize both financially and with reduced environmental impact if exact needs could be embedded in PSS offerings [5].

Standardization of the product portfolio is seen as a prerequisite to servitisation as one of the interviewees pointed out: *"…lack of the product standardization makes it difficult to offer standard services and track and compare their performances."*.

Operational. An evident challenge is the lack of knowledge and capabilities to drive the PSS development process [13]. For capital goods manufacturers, the challenge is to gather and determine data needed that would enable understanding customer needs and product usage insights, and consequently be a basis for more valuable offerings. An interview said: *"We realize the importance of having insights into how customers use our products, but we don't know what data are relevant to measure."*, and another said: *"Even if we had all the possible data, we wouldn't know how to make sense of it."*. Therefore, data analysis skills are seen as pivotal to develop new PSS offerings in a structured way. In practice, as one of the interviewees put it; *"…even the customers might not be able to express their need or how they use the products."*. The question is raised whether it is the customer's provider's role to enable data gathering.

Another concern is the willingness of a customer to share data with the manufacturer. A couple of interviewees stressed the customers' fears of legal and GDPR problems, as also indicated by numerous commentators [15]. A further notable barrier stated by the interviewees is a lack of resources to be proactive about offering combined solutions.

4 Discussion

Results Commentary. Largely similar patterns are recognized when comparing literature and empirical findings about drivers and barriers for the introduction of PSS. Certain exceptions are, however, observable both with respect to drivers and barriers. It is the depth of the empirical study that yields more concrete insights into perceived drivers and barriers in the company. Namely, if compared to literature, this empirical approach identifies many more tactical and operational drivers and barriers. This also seems to be related to the interviewees' position in the company, as they tend to think of operational barriers they would have in their position. That is deemed only natural but very valuable as such interviewees bring out concrete challenges and ideas to overcome them. Strategic employees, on the other hand, see many strategic drivers that are primarily related to sustainability and very few barriers.

It was difficult for managers at the operational level of the organization to find drivers for their actions. It is perceived that the motivation for action comes from a level above, either tactical or strategic. This observation brings even more attention to the importance of the top-down approach and clear communication of the PSS value coming from strategic and down to tactical and operational levels. Most of the drivers as perceived by interviewees were focused on what the company should expect to gain from PSS and only a few on what the customer gains. Furthermore, it is perceived that it most frequently the customer who is the cause of most of the barriers.

The access to the product and the ability to track its performance during the useful life is observed to be of pivotal importance, as this opens opportunities to build services, even on top of an already installed base of products. While PSS is not just a service built on top of the product, which is not inherently designed for it, this type of (so-called "wire-framing") approach is often seen as a way to test the market with new services. It is challenging to carry out product alterations once they are already at the customer, and significant changes would introduce unknown risks after the product is already installed. Therefore, moderate alterations only can be made in this way as pilot projects, in order to gain input to new PSS development projects.

As perceived by the authors, patterns can be observed when considering the interviewees' function in the company. When comparing interview answers, the most conspicuous divergence arose between the answers of interviewees with technical versus non-technical background. This difference primarily manifests in the sharpness of focus on the challenges by the technical staff rather than drivers, and their focus on the operational rather than strategic motives and obstacles. Hence, they weigh different challenges differently according to their technical nature. Another dimension to compare the answers from the interviewees is whether they perform a customer-facing function. Those who interact with customers are more certain that a customer is willing to share data and collaborate than those who do not have direct contact with customers.

The most recurrent theme of the interviews is the importance of knowing the customer and the importance of knowing the use phase of the product, and it is observed as crucial for the provision of PSS offerings. The opportunity to provide value within the lifetime of a capital good is perceived as immense by the interviewees, both financial in terms of savings for customers and earnings for the producer, but also environmental, with proper service and maintenance to extend to products' life and efficiency.

Actions Based on Results. It is considered that the result representation in Fig. 1 may serve as a canvas for drawing a roadmap of the action course for further PSS development. As a first step, practitioners would have to agree on the most important driver for the introduction of PSS. By making such a decision, all the lower-level drivers and barriers can be prioritized, that is, focused on achieving that strategic goal. Hence, even though there are still many barriers, some may be eliminated as tackling them will not bring the company any closer to achieving the strategic goal, and some are mitigated by the clear motivation on why they must be resolved on each level.

As depicted in Fig. 2, a preliminary roadmap can be drawn, connecting the most important drivers with the corresponding barriers starting from the main strategic goal indicated with the red circle. The process is then further guided through tactical and operational drivers and barriers to a single operational action.

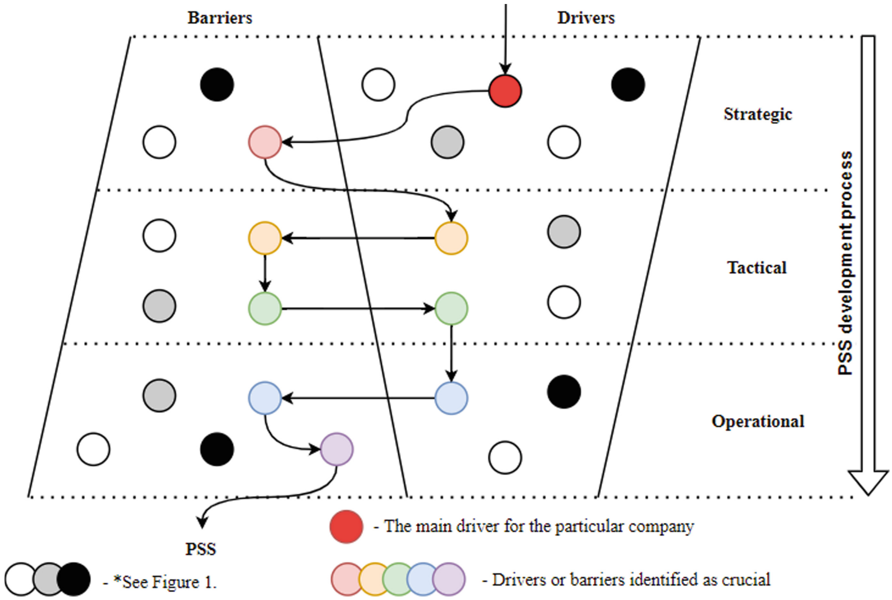

Fig. 2. Focusing the PSS development process with the help of drivers and barriers.

Depending on the impact that the addressing of a particular barrier will have on the main driver, the most impactful barriers may be selected to be solved. As the path progresses towards more operational challenges to solve, more drivers will be evident to the operational personnel, regarding why it is important to address those challenges. It can be said that barriers are translated in a process or the course of action. They serve to create and direct the PSS development process.

For the case company, as per Fig. 2, perceived dominant barriers in relation to the strategic driver of sustainability are the knowledge barriers about the connection between sustainability and service. On a tactical level, this can be translated into a driver that is the introduction of product upgrade services that will contribute to energy savings (yellow driver circle). There are other barriers on the same level, namely, the company has limited knowledge on the current energy performance of the product, consequently, there is a challenge on how to measure the performance after the upgrade (green barrier circle). There is another driver to track the product performance–to find out how customers use the product. Moving into operational drivers (blue driver circle), another motive to introduce a monitoring system would be to enable the gathering of different data points that could, in turn, help with optimizing other factors than the energy use. An operational barrier here is to discern what data is relevant to measure and stemming from it is the competence barrier to analyze the gathered data. Following such a train of thought, as in Fig. 2, it could be deducted that knowing the customer and the products' use phase would have a significant impact on the success of the PSS implementation. Those challenges are easily tied to the traditional view of product development in manufacturing companies, where products are not designed for ease of use and serviceability. Opportunities to address those challenges are possible through mapping user activity cycles, service blueprinting and usage monitoring. Therefore, it seems that the most sustainably potent form of PSS for capital goods manufacturing companies is inseparable from the digitalization process and data gathering.

Limitations. This approach is proposed based on a single case study; thus, it has a very specific application, and it is not possible to draw generic conclusions for all capital goods manufacturing firms. The value of such a study manifests in the depth of insight achievable for an individual practitioner, as well as to showcase the importance of drivers and barriers that were not found empirically to the case company. Further studies in other cases will elicit to what extent the approach might be generalizable. The model depicted in Fig. 2 might be tested by conducting a series of interviews in other companies, as it is done in this study, to elicit drivers and barriers from different levels of the organization. Those can then be used to lay down or streamline the course of action in the process in the PSS development with respect to the company's strategic goals.

5 Conclusion

Instead of focusing on solely top management input, this empirical research brings a 360-degree approach within the company to clarify the pivotal motives and challenges for the introduction of PSS, both from the strategic, tactical and operational levels.

The purpose of such a business-wide investigation of motives and challenges is manifold; to get an understanding of the interaction and viewpoints from different parts of the organization; to elicit and communicate ideas across the organization; to spot previously unforeseen opportunities; not to overlook some of the challenges, and to make more informed and inclusive decisions about the focus of PSS development in the organization. Practitioners may, therefore, replicate this approach to gauge themselves internally before reaching out to the customers having considered internal dialogues.

Different parts of the organization perceive drivers and barriers for the introduction of PSS differently. Various viewpoints seem to be connected to the nature and the seniority of the interviewees' functions, where noticeable differences in answers are observed depending on the technical or non-technical nature of the function and whether the participants were interacting directly with the customers or not.

Guided by the most recurring interviewee observations paired with literature research, further research steps will be the involvement of customers and the data to be gathered from the installed base of the products in the PSS co-development process. The intention is, therefore, to adopt a customer-oriented and data-driven approach motivated by sustainable agenda that would yield the most valuable solutions both for the customer and the PSS provider.

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Review Article

Designing sustainable product-service systems: A generic process model for the early stages

David Sarancic [a,*], Daniela C.A. Pigosso [a], Giuditta Pezzotta [b], Fabiana Pirola [b], Tim C. McAloone [a]

[a] Technical University of Denmark (DTU), Department of Mechanical Engineering, Nils Koppels Allé 404, 2800 Kgs. Lyngby, Denmark
[b] University of Bergamo, Department of Management, Information and Production Engineering, Viale Marconi 5, Dalmine, BG 24044, Italy

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ABSTRACT

The design of Product-Service Systems (PSS) in manufacturing companies has been widely researched over the past three decades, with contributions from various backgrounds. However, the multidisciplinary field led to the development of disparate approaches for PSS design, which furthermore deficiently include sustainability considerations. Such discord hinders PSS uptake in industry due to the unclarity of which process to use and crucial matters to consider. This paper aims to propose a generic process model to describe the early stage of the PSS design, which is the most influential phase for the success of the PSS offering throughout its life cycle, concerning the three dimensions of sustainability. The proposed generic process model addresses early-stage PSS design in three phases and considers seven clusters of entities through five activities. To achieve this aim, existing approaches for PSS design were identified through a systematic literature review, yielding a comprehensive overview of existing approaches distilled with respect to their content, the actions they propose and the sustainability principles they discuss. The systematic review was then followed by in-depth content analysis using widely adopted methodologies in design research and manufacturing companies for process decomposition and consequently synthesis, resulting in the proposed systematic generic process model for the early-stage design of sustainable PSS. The proposed process model was further examined concerning its use implications, limitations, and potential implementation steps.

Contents

* Corresponding author.
E-mail address: dasar@dtu.dk (D. Sarancic).

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1. Introduction

The motivation to design Product-Service Systems (PSS) has been changing since the concept's inception often accredited to Goedkoop et al. (1999). Early research into the field was driven by the aim of achieving the environmental sustainability potential of PSS (Mont, 2004). Henceforth, numerous authors from other fields (e.g. engineering design, business management, information systems) have joined the discourse (Boehm and Thomas, 2013; Pezzotta et al., 2015), and a multitude of approaches for PSS design have been developed (Cavalieri and Pezzotta, 2012; Qu et al., 2016; Vasantha et al., 2012), yet with inconsistent terminology and objectives (Peruzzini and Wiesner, 2020). Although the developed approaches address many important gaps, studies of companies attempting to utilise them show disappointing success rates, with respect to being able to deliver both profitable (Neely, 2008) and environmentally sustainable (Bech et al., 2019) offerings to the market.

PSS is currently enjoying revived attention in up-to-date literature, mostly due to advances in digital technology and a focus on circular economy (CE) (Pirola et al., 2020) as a means to achieving sustainability (Kjaer et al., 2018). It is expected that the intense period of development of PSS approaches will culminate in the coming years with an accentuated emphasis on consolidation and integration of existing approaches (McAloone and Pigosso, 2017; Pigosso et al., 2015), which is the main focus of this research. Such PSS business models have also been recognised by the European Commission as one of the key instruments to consider toward the 2030 sustainability targets (European Commission, 2015, 2019).

Already a decade ago, Boehm and Thomas (2013) underlined that the major task of future contributions in the PSS field should include a reach across disciplinary boundaries (e.g. engineering design and business management) involved in PSS design. Despite this assertion, the literature is sparse on the integration of PSS development activities (Peruzzini and Wiesner, 2020), particularly in a collaborative way at the early stage of design (Pezzotta et al., 2018). There is currently a lack of approaches to support the design of PSS, especially when conceptualising and carrying out the early PSS design stages (Barravecchia et al., 2020); some suggestions are to be found within the literature, but are spread and remain largely at a qualitative level (Sakao and Neramballi, 2020). The process models reported in the literature are dissimilar in the activities they propose (Marques et al., 2016), and sustainability is tackled sporadically and superficially (Moro et al., 2022; Qu et al., 2016).

No comprehensive or generic framework has been found for early-stage PSS design that unifies existing proposals in a synergetic way and no early-stage PSS design process model can be treated as a de facto standard in industry, which leaves theoretical contributions untested and uncomplete (Chiu et al., 2018; Clayton et al., 2012; Guillon et al., 2021; Sakao and Neramballi, 2020). This research, therefore, sets out to identify patterns in the existing approaches to the early stage of sustainable PSS design and propose a generic process model, as merely coalescing existing methods and process models is unlikely to bring novelty on its own (Song and Sakao, 2017).

The following sections elaborate on the state-of-the-art literature (Section 2), describe the methodology (Section 3), present the phases and entities that constitute the generic process model along with the necessary sustainability considerations (Section 4), discuss the key findings and insights (Section 5), and conclude with clearly outlined contributions (Section 6).

2. Background

2.1. PSS design

PSS is a life cycle-oriented marketable blend of tangible and intangible offerings, supported by the infrastructure and the actor-network, designed to deliver more value than traditional transactional offerings (Mont, 2004). PSS design is the interdisciplinary process of ideating, selecting and developing a PSS concept into an offering (Vasantha et al., 2012), and is an integral part of service-related business development (Bech et al., 2019).

PSS design implies a particularly wide area of intervention when compared to traditional product design (Morelli, 2006), as more knowledge domains need to be involved and more complexity is introduced (Nemoto et al., 2015; Shimomura et al., 2015). This complexity can largely be attributed to the heterogeneity of design elements and their variants to be concurrently considered (Barravecchia et al., 2020). In addition, the differentiation between the PSS design task and the business development activity in a company becomes increasingly blurred, as PSS presents itself in different patterns than traditional product development or service development (Maussang et al., 2009).

Despite its many-year development in different fields, only meagre research has been conducted on how to actually support the PSS design process in practice (Haber and Fargnoli, 2017). Incipient considerations of PSS design support propose a four-stage process (Clayton et al., 2012), often comparable to the stages devised in traditional product development reference models, such as Pahl and Beitz (2004): planning and clarifying; conceptual design; embodiment design; and detailed design. The intricate activities within each stage of the PSS design process are not well clarified and diverge greatly in the literature (Trevisan and Brissaud, 2016), thus making it difficult to set the boundaries on the early-stage PSS design (Rosa et al., 2017). Contributing authors from mixed backgrounds propose approaches with disparate phases and activities in the design process (Marques et al., 2016). The approaches identified predominantly omit to detail the early design process beyond the description of high-level phases (Haber and Fargnoli, 2017) and they have different starting and ending points (Clayton et al., 2012). As a result, PSS design processes continue to be vague in the literature.

2.2. The lack of support for the early-stage PSS design

As established in the design science literature, the early-stage PSS design encompasses planning and conceptualisation stages (Rosa et al., 2021) that result in an assessable PSS concept (Welp and Sadek, 2008).

The early stage of PSS design ending with conceptualisation plays a key role in PSS design (Alonso-Rasgado et al., 2004; Peruzzini and Wiesner, 2020), as it works as a compass in implementation and defines the value to be provided to beneficiaries (Kimita et al., 2009). The early design stage leads to the definition of new PSS concepts that can satisfy stakeholders' needs and identify the required resources to do so (Rondini et al., 2016). Since the existing definitions of the PSS concept as the output of the early design phases have discrepancies (see e.g. Sutanto et al. (2015) or Song and Sakao (2017)), in this research, the PSS concept is defined as: "an actionable (implementable) and assessable (screenable) design proposal describing the total solution including the system's composition, its functionalities and business model that fulfil the requirements of the involved actor-network".

In contrast to embodiment and detailed design, the early-stage PSS design deals primarily with what should be offered, rather than how to deliver the offering, and therefore focuses on the definition of the product functions, the service elements, the infrastructure and the network of players, as well as their interaction (Barravecchia et al., 2020). In early-stage PSS design, the system that is to be designed ought to be analysed within a wider beneficiary's system than in pure product design, meaning that PSS design involves many more actors and systems managed by those actors (Trevisan and Brissaud, 2016).

Important characteristics of early-stage PSS design include the structuring of innovative thinking for concept generation (Yang and Xing, 2013) and the high volatility and unavailability of early-design information (Sousa-Zomer and Miguel, 2017), where relevant information may also get ignored (Rosa et al., 2021). The applicability of quantitative methods (Bertoni and Bertoni, 2020) and the ability to use data-intensive techniques is limited (Rondini et al., 2020). Furthermore, the early-stage PSS design is often limited to functional analysis in which stakeholders' involvement and product-service compatibility are overlooked (Haber and Fargnoli, 2017; Maussang et al., 2009).

There is a greater opportunity in early-stage PSS design to use systematic approaches for avoiding sub-optimal decisions concerning cost and risk (Bertoni et al., 2019) and to prevent resource allocation on design concepts with doubtful odds of success (Tran and Park, 2016). Lindahl et al. (2006) point out that it is crucial to learn as much as possible about the evolving PSS early in the development process because the market success of PSS can be attributed to decisions taken in the early stages, as that is when the changes are the least expensive (Schmidt et al., 2015).

Despite its criticalities and opportunities, early-stage PSS design in manufacturing companies is predominantly characterised by intuitive approaches (Aurich et al., 2006) supported by many different models (Rondini et al., 2016), as existing approaches are difficult to implement in an industrial context (Andriankaja et al., 2016). The result is often an inefficient and erroneous early-stage design process where PSS designers largely rely on their experience (Yang and Xing, 2013) and abilities rather than systematic approaches (Kim and Yoon, 2012).

Existing models for early-stage PSS design advise disparate phases (Marques et al., 2016) and are largely focused just on a part of the complete early-stage PSS design, e.g. a business model (Adrodegari et al., 2017) or PSS requirements (Sousa-Zomer and Miguel, 2017). Therefore, the individual methods seldomly resolve the problem of PSS concept generation on their own (Kim and Yoon, 2012; Sousa-Zomer and Miguel, 2017). Moreover, the majority of the process models have a high level of abstraction of phases which are separated by instances of evaluation and decision-making (gates). Thus, process models remain incomplete and undetailed (Haber and Fargnoli, 2017), and in most cases, inefficient (Sakao et al., 2020).

Predefined generic PSS design process models have the potential to support companies in systematically capitalising on positive effects and avoiding negative effects of PSS (Aurich et al., 2006; Vasantha et al., 2015). Early-stage PSS design is considered to be best facilitated through a systematic approach (Yang and Xing, 2013) that can be adjustable for individual practitioner purposes (Becker et al., 2010).

2.3. Sustainability in early-stage PSS design

PSS could be powerful enablers of sustainability, both economically, environmentally and socially (Aurich et al., 2006; Sarancic et al., 2022). PSS has the potential to accomplish a positive sustainability impact in the triple-bottom-line (TBL) (Elkington, 1998; Isil and Hernke, 2017; Purvis et al., 2019), through e.g. stable and predictable revenue over time, prolonged product useful life and greater customer acceptance (Chiu et al., 2018). However, PSS offerings are not intrinsically sustainable (de Jesus Pacheco et al., 2022) and their sustainability performance remains case-dependent (Sutanto et al., 2015).

Even though PSS has been discussed as a direct means toward achieving sustainability (Kjaer et al., 2018; Koide et al., 2022), PSS offerings are not by default more sustainable than the individual product (Bech et al., 2019; Tukker, 2015) and some PSS offerings may even produce unintended side effects, commonly referred to as rebound effects (Metic and Pigosso, 2022), in any of the three dimensions of sustainability (Doualle et al., 2015).

Sustainability considerations should be made throughout the PSS design process, starting in the early stages, which determine most of its sustainability impact (Pigosso and McAloone, 2015; Sousa-Zomer and Miguel, 2017) and where the greatest opportunities for more sustainable solutions lay (Maxwell and Van der Vorst, 2003). However, this is also the stage where the least is known about PSS and where manufacturing companies face challenges (Kolling et al., 2022). Therefore, support for companies is needed from a process perspective in sustainable PSS design (Pieroni et al., 2017).

Current models for early-stage PSS design do not fully support the creation of the TBL sustainable PSS offerings, and few approaches found in the past literature incorporate sustainability principles in the early-stage PSS design (Moro et al., 2022) while a need for such approaches has been long vocalised in literature (Ny et al., 2013). Early customer involvement is also pivotal to connecting the value network between various stakeholders and embedding sustainability visions in early-stage PSS design, thus tackling social sustainability (Chen, 2018).

A habitual misbelief prevails in the PSS design literature that following a PSS design process instead of a mere product design process will automatically yield a more sustainable offering, but that is not necessarily the case (Tukker, 2015). Although many approaches claim to produce more sustainable offerings, few explicitly incorporate sustainability principles and even fewer in the early-stage PSS design (Sousa-Zomer and Miguel, 2017). When the sustainability principles are incorporated into the design process, a more sustainable outcome offering can be expected (Pigosso et al., 2013).

The instructions on how and when to pragmatically embody these considerations in early-stage PSS design process remain vague in the extant approaches. Sustainability must be considered throughout the process and in many constituent entities and activities, not only in the evaluation, as mostly proposed in the literature (Qu et al., 2016). Even those sparse methods that propose sustainability considerations in the early-stage PSS design in the literature tend to be ajar in between each other and are most often not suited for the early stages of design with so many unknowns (Doualle et al., 2020). Therefore, despite numerous proposals in the literature, a comprehensive process for sustainability-integrated early-stage PSS design remains unclear.

3. Methodology

The research commenced with the identification of the research gap, i.e., the need for a generic process model for the early-stage design of sustainable PSS, ahead of conducting a systematic literature review (SLR) (de Almeida Biolchini et al., 2007). To set the direction of SLR, dominant literature reviews on PSS design (Boehm and Thomas, 2013; Cavalieri and Pezzotta, 2012; Clayton et al., 2012; Pirola et al., 2020; Qu et al., 2016; Sakao and Neramballi, 2020; Tukker, 2015; Vasantha et al.,

2012) were examined to get an overview of the most recurrent approaches and adopted methods.

Based on the overall objective, four research questions (RQ) to be answered through SLR were formulated:

- RQ1 – What are the main phases and activities conducted in the existing early-stage PSS design approaches?
- RQ2 – What constituent entities of early-stage PSS design do the existing design approaches consider?
- RQ3 – How to unify the existing perspectives in a generic, yet readily applicable process model for early-stage PSS design?
- RQ4 – What are the sustainability considerations in the existing early-stage PSS design approaches and how to incorporate them into the proposed generic process model?

The research questions naturally progress from process to content inquiry of the existing approaches. The first two questions do not focus on approaches that explicitly include sustainability considerations, to widen the search. The third question synthesises the answers to the first two questions in a new process model, while the fourth question inquires deeper into the sustainability aspects of early-stage PSS design. To answer the research questions, an SLR was conducted following a protocol devised by de Almeida Biolchini et al. (2007), which comprises three activities: data collection, analysis and reporting.

3.1. Data collection

Data collection consisted of a search and selection procedure (Fig. 1) of available publications in Scopus. After conducting the initial search in both Scopus and Web of Science (WoS) databases, Scopus was selected due to the fact that results yielded from the latter in a great measure represented a subset of the results from Scopus, therefore a more comprehensive database was selected.

The final search was carried out in August 2022 and resulted in 876 unique publications. The elicited publications were subject to two filters: (1) the title, abstract and keywords; and (2) a full read of selected publications to determine whether they satisfied the inclusion criteria:

1. The study must report at least one method, tool, or approach to support early-stage PSS design or an integrated PSS development process described in sufficient detail.
2. The study must relate to manufacturing companies.

Snowballing (Wohlin, 2014) was performed to identify publications falling outside of the database search (through cross-reference), thus also capturing the publications from the WoS, which resulted in the identification of 44 additional publications. The same filters and criteria were applied to select the publications obtained initially from the Scopus database and to the publications identified through snowballing. The snowballing procedure continues until the saturation point, i.e., the exhaustion of available publications that satisfy the above criteria.

In total, 96 studies were selected (full list in the Supplementary material).

Although the search string focused on early-stage PSS design and conceptual design, which are often used interchangeably in literature (Welp and Sadek, 2008), the final set of publications reached through snowballing includes many of the approaches with a much wider scope than early-stage PSS design (e.g. Van Halen et al., 2005; Tukker and Tischner, 2006). Those renowned publications in a great measure

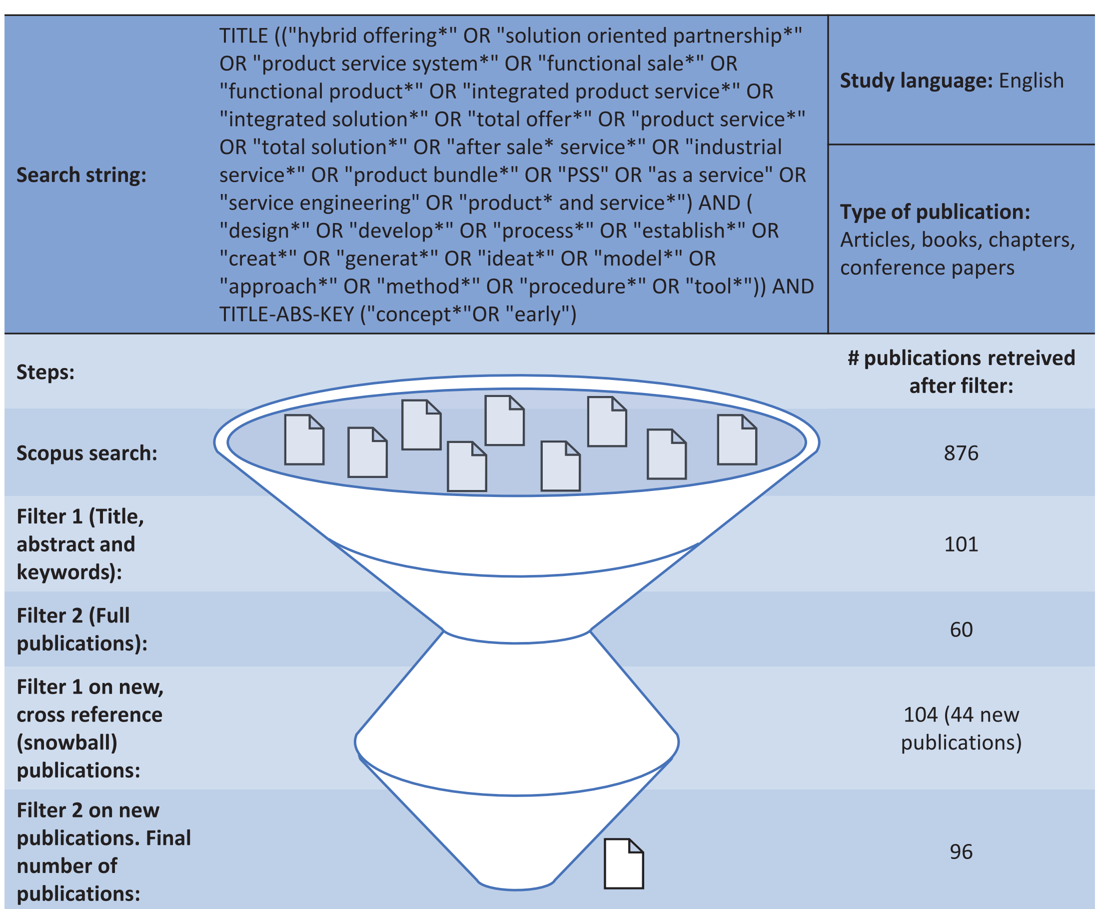


Fig. 1. Systematic literature review search parameters, process, and results.

contributed to the completeness and boundary setting of the early-stage PSS design process.

3.2. Data analysis

From the set of 96 selected publications, 96 approaches were identified as potentially relevant for early-stage PSS design. To answer the first two research questions, content analysis was conducted, employing coding and thematic organisation (Dresch et al., 2015) of constituent entities, activities and tools, which enabled comparisons across approaches despite disparate nomenclatures. The categorisation was achieved by observing patterns that emerged during the data analysis and related activities. Here, constituent entities were grouped through emergent pattern identification (Yin, 2003). The constituent entities imply objects of design or consideration which can be grouped in a cluster, the activities are the necessary actions to conduct during the design process, and the tools are design supports that can facilitate the design process to yield optimal returns (Rondini et al., 2016).

The theoretical framework selected to aid the analysis of the data was IDEF0 (ISO 31320-1, 2012). IDEF0 is a functional modelling language that uses Inputs, Controls, Outputs, and Mechanisms (ICOM) for process decomposition and mapping which enabled the achievement of a baseline for the comparison across different elicited approaches. IDEF0 supports a methodical approach to PSS design (Morelli, 2006), ensuring success in both product, service and PSS design (Trevisan and Brissaud, 2016), and wide adoption in industrial companies. Furthermore, IDEF0 aligns well with the Theory of Technical Systems (TTS) (Hubka and Eder, 1988), an adjacent theory in the design of technical systems useful as a rational basis for examining engineering design processes. The approaches elicited from the literature were deconstructed using IDEF0 and used as inputs to contrive a generic process model for early-stage PSS design.

Following the analysis of all the selected approaches, eight of them are selected for an in-depth analysis, based on four criteria (focus on sustainability, validated industrial applicability, level of detail, and the number of citations), to serve as a mainframe for the development of the generic process model. Those criteria were selected because the paper aims to ensure the widespread applicability of the generic process model in industry, the inclusion of sustainability considerations, as well as sufficient detail of the model.

3.3. Data synthesis

To answer the third research question, a unified and generic process model for early-stage PSS design has been proposed following the structure of the Rational Unified Process (RUP) (Kruchten, 2000). The RUP devises a structured time-based evolution of a process in which various constituent entities need to be considered at different moments, thus enabling effort prioritisation over time.

The findings from the analysed approaches were synthesised to yield a generic process model and a recommendation of the sequence of phases, activities, and constituent entities to be considered during early-stage PSS design (Section 4.3). The synthesised process model was initially verified by a panel of academic experts and industry specialists from a manufacturing company, through a series of meetings and feedback sessions.

The proposed process model served as a canvas for answering the fourth research question, as it was developed in such a way that enables the mapping of sustainability considerations throughout early-stage PSS design.

4. Results

The identified approaches are significantly dissimilar in three ways, relating to; (i) the granularity level of phases' descriptions and the number of phases/activities; (ii) the number and types of constituent entities of early-stage PSS design and (iii) the level of inclusion of sustainability considerations. The further sections elaborate on these three points, while more detailed descriptive findings can be found in the Supplementary material.

4.1. Phases and activities of the existing approaches to early-stage PSS design

Of the 96 approaches, only eight have a comprehensive consideration of the early-stage PSS design, i.e. they consider all the cluster entities defined in Section 4.2, the TBL and life cycle thinking (see Supplementary material for more detail). Those eight approaches were examined more closely (Fig. 2) and compared with respect to four criteria to select the mainframe of the generic process model for early-stage PSS design:

C1. Focus on sustainability
C2. Validated industrial applicability
C3. Level of detail in terms of all the entities considered
C4. Number of citations in the literature

Most of the approaches have a wider focus than just the early-stage PSS design. Although employing quite different nomenclature and the scope of the phases, the eight approaches have many similarities regarding the overall process and considerations they propose. The similarities manifest in the cadence of activities of most approaches, but also in the contents of the phases (e.g. most approaches agree on the contents of the ideation phase, whether they call it idea development, idea generation and evaluation or identification of products and services).

Subject to the four criteria, the approaches proposed by Van Halen et al. (2005), and Tukker and Tischner (2006) proved the most relevant. Due to their resemblance in terms of proposed phases (Fig. 2), a similar mainframe focused on early-stage PSS design consisting of three phases was adopted, namely: (i) strategic planning, (ii) exploring opportunities and (iii) PSS concept development which include activities in the eight analysed approaches until the red line indicated in Fig. 2. The name of the first phase has not been adopted from any of the existing approaches but was instead adapted to more closely reflect the contents of that phase which are deemed wider than just analysis or an introduction.

The researchers devise different process models i.e. phases and activities to design PSS concepts and their constituent entities, however, they use similar workflows to transform inputs into outputs no matter the constituent entity. Even though the existing early-stage PSS design literature does not follow any set process, the sequence of actions or nomenclature concerning activities needed to design the constituent entities is similar. The analysis of the existing approaches revealed the pattern of the most common activities, usually described with one of the following five action words or their synonyms in chronological order: identification, analysis, definition, selection and refinement. Those five activities in a workflow are, therefore, needed to design any of the constituent elements (e.g. identification, analysis, definition, selection, and refinement of requirements), and are one of the key elements to devise a generic process model (Section 4.3).

4.2. Entities to consider in early-stage PSS design

The following sub-sections elaborate on the constituent entities of early-stage PSS design, elicited from the 96 relevant approaches and classified into seven overarching clusters (Table 1): business model, the network of actors, requirements, functions, offerings, structure, and the plan for implementation, as elicited from the literature.

4.2.1. Business model

A business model describes how a company creates, captures and delivers value (Pieroni et al., 2019a). The core dimension that drives Business Model Innovation (BMI) is the value proposition, which indicates the value that the provider may offer to all the actors in the network through PSS (Fernandes et al., 2020). Most of the value of a

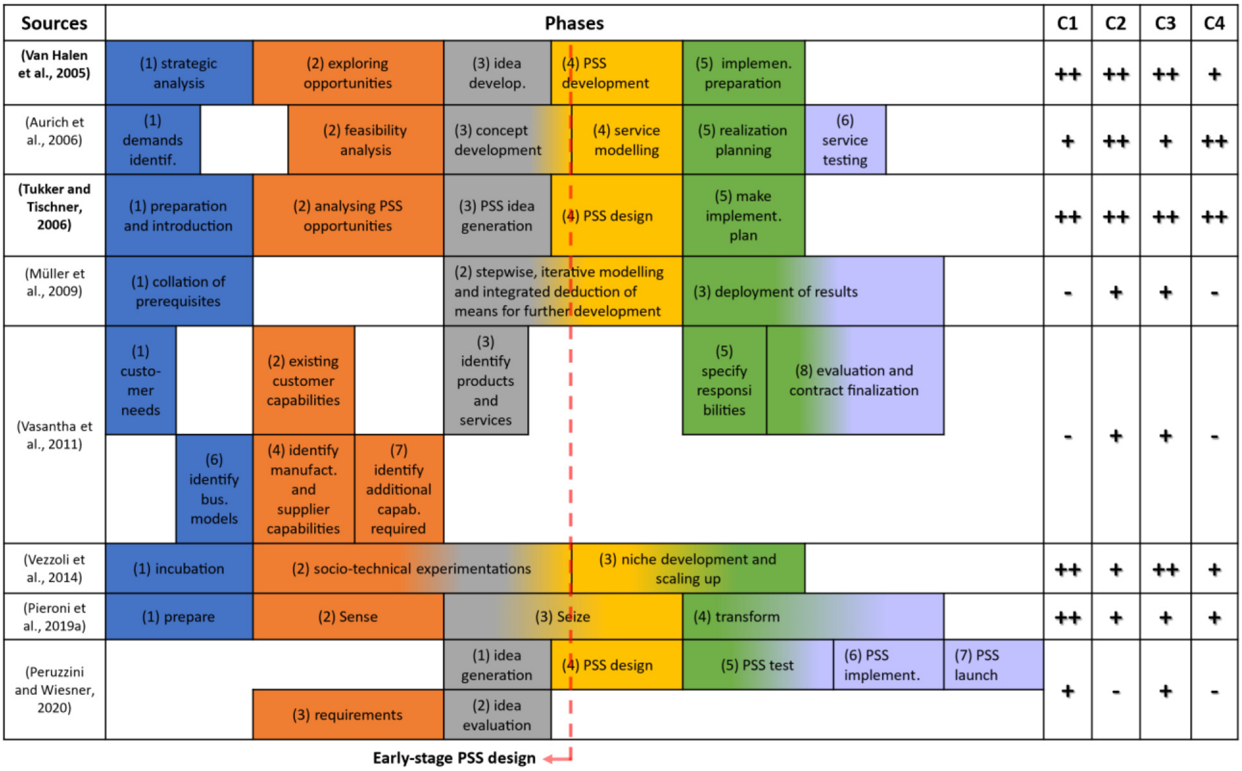


Fig. 2. The phases in the eight most comprehensive approaches. The phases are colour-coded according to their contents, in comparison to the approach in the first row. The approaches are rated according to the level to which they satisfy the four criteria. The end of the early-stage PSS design is indicated with the red line. Legend: (++) satisfy to great extent, (+) satisfy to some extent, (−) poorly satisfy.

PSS concept is defined in the early stages (Kimita et al., 2009; Sakao and Neramballi, 2020), but it is difficult to anticipate the actual value for the involved actors at this early point (Panarotto et al., 2017), as value perceptions vary and are individual to each recipient (Song and Sakao, 2017) and can only be understood when the offering is in use (Meier et al., 2011).

Table 1
Constituent entities of early-stage PSS design clustered, as elicited from the literature.

Clusters	Cluster descriptions	Constituent entities
Business model	The way a company creates, captures, and delivers value.	Value proposition, use scenarios
Network of actors	All the external stakeholders' relationships and interactions in an ecosystem which engages in PSS provision.	Customers, partners, suppliers, and competitors
Requirements	The minimum acceptable standards that the PSS concept should satisfy over its life cycle and according to the TBL.	Demand, wishes, needs, specifications, engineering characteristics, contradictions
Functions	A set of qualities with a particular purpose associated with the PSS offering that can be decomposed and accredited to different elements of the concept.	Functional unit (FU), sub-functions, performance, satisfaction unit
Offerings	Product and service components, their modules together with architectures, interfaces, and the related processes.	Product (the main tangible artefact) and service (intangible artefact), PSS delivery process
Structure	All the support resources and their internal organisation that are enabling the delivery of the value of the offering.	Infrastructure (periphery, support systems), organisational structure, capabilities, resources, logistics
Plan for implementation	A roadmap with a timeline of required activities to realise the conceived PSS concept with assigned responsibilities.	Deployment plans, responsibilities, roles, project key performance indicators

Many alternative value propositions might look promising, therefore, to gain a deeper insight into their potential, the generation of several alternative use scenarios can be conducted to develop the idea further in a particular context (Maussang et al., 2009). Scenario generation is one of the critical steps in early-stage PSS design (Yang and Xing, 2013) as it is a source of a variety of receiver behaviours to be studied when delivering the service and where the receiver state parameters (RSPs) are changed (Sakao and Shimomura, 2007). The use of scenarios implies devising a temporal organisation of actions that actors take in a particular context (Trevisan and Brissaud, 2016), enabling designers to investigate the way actors might behave (Maussang et al., 2009).

The business model cluster and its constituent entities, elaborated using IDEF0 throughout the three phases of early-stage PSS design, can be seen in Fig. 3.

4.2.2. Network of actors

It is considered that the value beneficiaries seek can be most effectively delivered by the homogenisation of offerings of a network of cooperating companies (Pawar et al., 2009), which must be done early in the PSS design (Mougaard et al., 2012). Stakeholders' involvement is often disregarded in the existing approaches (Haber and Fargnoli, 2017), and PSS designers plead for approaches that incorporate stakeholder preferences in PSS design (Vasantha et al., 2012). The importance of considering the structure of relationships within the network stems from the possibility to identify opportunities for new constellations of revenue, information and resources required for innovating and sustaining a PSS offering (Mougaard et al., 2012), as well as its optimal operation (Alonso-Rasgado et al., 2004).

The network of actors includes several categories of external participants involved in early-stage PSS design (such as customers, partners,

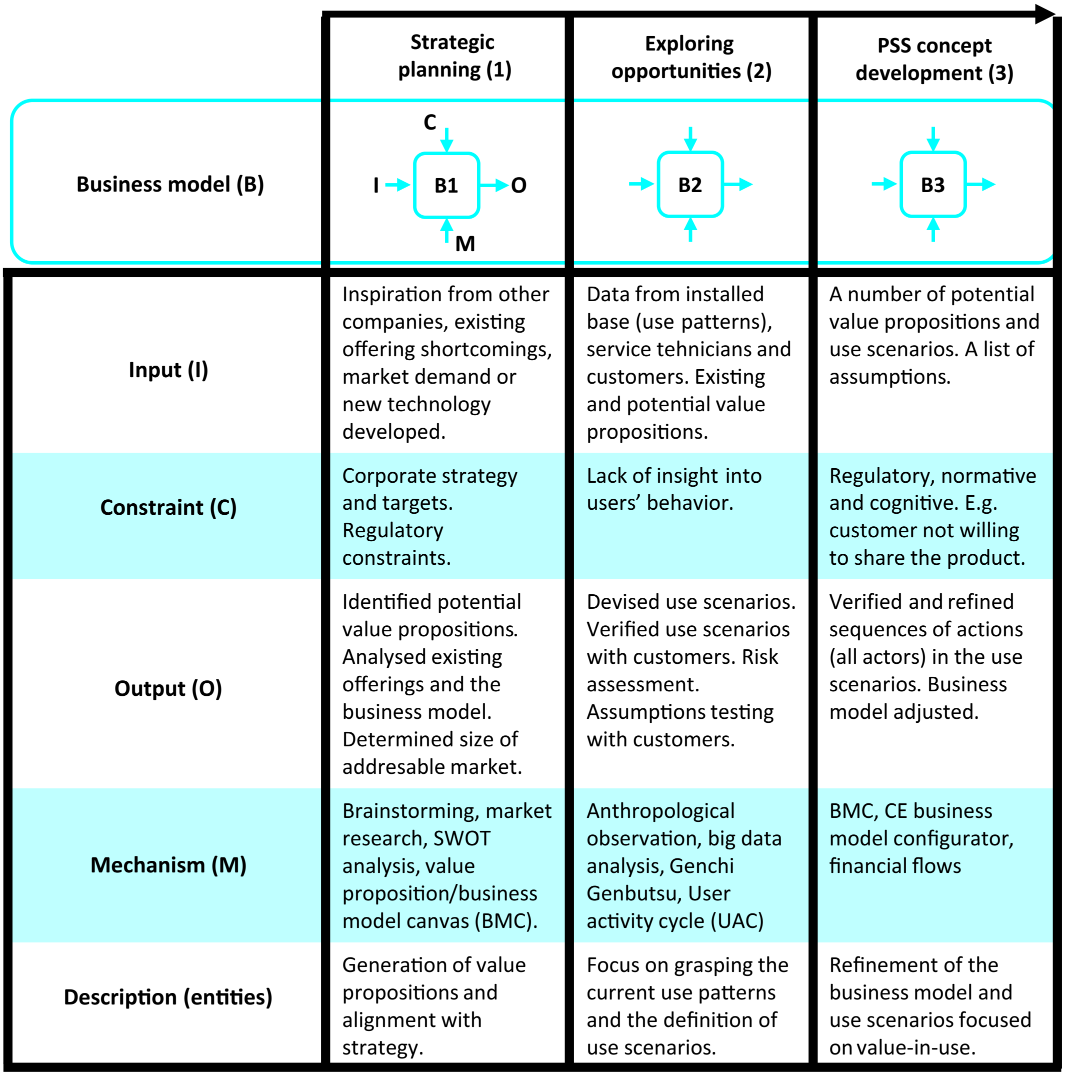


Fig. 3. Business model cluster mapped into ICOM notation in the three phases of early-stage PSS design.

suppliers and competitors) (Sakao and Neramballi, 2020). This cluster focuses primarily on external relationships in a wider sense than customarily considered in BMI. The internal organisational structure is considered a part of the structure cluster (Section 4.2.6), as it is where the PSS-providing company has the direct responsibility to design it while the external network can only be influenced. Hence, the network of actors could be defined as a conglomeration of all upstream and downstream offering value chain actors involved in the co-creation of the PSS offering.

Customers and users are not solely the targeted consumers, but they represent an invaluable source of insights to be actively utilised in PSS design (prosumers) (Mougaard et al., 2012), and so do the partners (Maussang et al., 2009).

Alongside the community directly interfacing with the PSS offering, there is a wide range of both governmental and non-governmental potential partners essential to be mapped and aligned (Rosa et al., 2016) including, but not limited to the authorities, legal bodies, and conservation institutions (Lindahl et al., 2006), and service contractors, energy providers, financing institutions and consultants (Trevisan and Brissaud, 2016), respectively.

Suppliers of the physical materials and sub-parts which will build up the tangible parts of the PSS offering as well as the supporting infrastructure (Section 4.2.6) have to be carefully contemplated due to: the risk of extended commitments necessary for cost-effective component delivery (Alonso-Rasgado et al., 2004), environmental impact and transparency in their supply chain, and timely and reliable delivery (Maxwell and Van der Vorst, 2003).

Competitors are most often a source of learning and uncovering unserved market spaces for a PSS designer (Rondini et al., 2016). In some cases, however, competing companies can partner up for the benefit of both in terms of shared costs of transport or operations, or in certain market segments where they do not compete directly (Neugebauer et al., 2013).

Therefore, the significance of the various actors in the network is manifold in terms of their roles and potential contributions to the creation of value, and thoughtful selection and planning of actors' interventions in the early-stage PSS design can have a profound impact on the success of PSS offerings.

The network of actors' cluster and its constituent entities, elaborated using IDEF0 throughout the three phases of early-stage PSS design, can be seen in Fig. 4.

4.2.3. Stakeholders requirements

Customer needs in a great measure determine the PSS configuration (Pawar et al., 2009) and their elicitation and formalisation in the early stages are often considered an input for the conceptual design of PSS (Song and Sakao, 2017). However, due to the vagueness of PSS innovation, the requirements cannot be fully defined before the PSS concept

	Strategic planning (1)	Exploring opportunities (2)	PSS concept development (3)
Network of actors (N)	C, I → N1 → O, M	N2	N3
Input (I)	Pool of existing customers, partners, suppliers. Competitor screening.	Actors' wishes and relationships. Criteria for allocation of tasks to actors (e.g., market power, competencies, roles).	Final list of actors and their interactions, personas and customer segments, and their criticalities.
Constraint (C)	Restriction on collaboration in certain geographies or with uncertified suppliers.	Relationships between all the actors in the existing market.	Actors' willingness to share information.
Output (O)	Potential actors, roles and relationships (customers, partners (service, financial, legal, governmental, non-governmental), suppliers and competitors.	Customer segments and actors' personas defined (buyer and user). Defined goals and interactions of all actors. Supply chain dynamics analysed.	Involved actors' roles and responsibilities verified.
Mechanism (M)	Ecosystem map, UAC, competition scouting, supplier mapping.	Persona model, activity modelling cycle (AMC), sentiment analysis, interviews, surveys.	Interviews and workshops with actors.
Description (entities)	Identification and analysis of actors and their relationships.	Prioritisation of actors based on their wishes and capabilities.	Refinement of the actor network with a focus on performance measurement and criticalities.

Fig. 4. Network of actors cluster mapped into ICOM notation in the three phases of early-stage PSS design.

development phase begins, therefore understanding customer needs remains a major challenge as many needs are tacit and change over time (Rexfelt and Hiort Af Ornäs, 2009). For that reason, continuous requirement elicitation starting from an early phase from not only customers but all involved stakeholders has been heralded as one of the pivotal factors in successful early-stage PSS design (Sousa-Zomer and Miguel, 2017). Apart from a larger number of requirement demanders, the requirement definition for PSS implies a broad inquiry into more than just technical requirements to support early-stage decision-making (Bertoni et al., 2013). Rather, it requires consideration of the whole system-in-use, i.e. the use context to identify "the need behind the need" (Tukker and Tischner, 2006), which comes in contrast to the focus on just product and service requirements where scant information can be obtained (Hussain et al., 2012). Therefore, an integrated approach to need elicitation and requirement consolidation is required (Sutanto et al., 2015), one that is focused on the requested function-in-context (see Section 4.2.4).

Within this cluster of entities, another critical activity is the translation of the requirements into measurable engineering characteristics or specifications and their prioritisation (Geng et al., 2010; Sousa-Zomer and Miguel, 2017). These specifications ultimately determine the performance measurements and the constraints of the offering in the sense of their operating boundaries (constraints) and forbidden design features for whatever reason (Maussang et al., 2009). The definition of the specifications almost inevitably causes a conflict between them (Kim and Yoon, 2012), where the improvement of one parameter causes the deterioration of the other (Yang and Xing, 2013). The resolvement of these contradictions shows great promise in early-stage PSS design (Song and Sakao, 2017).

The requirements cluster and its constituent entities, elaborated using IDEF0 throughout the three phases of early-stage PSS design, can be seen in Fig. 5.

4.2.4. Life cycle functionality

The consideration of functionality during the complete life cycle can enhance the overall performance of PSS (Song and Sakao, 2017). This consideration should happen concurrently with requirement elicitation, by stating the requirements on the requested function, rather than in the product- or service-focused domain (Lindahl et al., 2006). Zhang (2013) extends this line of thinking by referring to PSS performance consisting of the function and its quality, which is the expression of function level and its availability over time. Sousa-Zomer and Miguel (2017) argue that even the definition of engineering characteristics must be considered in the functional domain because the final functionality satisfying the customer should be the inception of business development (Rexfelt and Hiort Af Ornäs, 2009).

Functional analysis (Kim and Yoon, 2012), i.e. the elaboration of the PSS function into its sub-functions is seen as a step in a gradual process toward the generation of a comprehensive PSS concept (Haber and Fargnoli, 2017). This consideration is not limited only to the function that the main offering delivers (Kimita et al., 2009), but also the set of functions that enable its delivery, executed either by the supporting

	Strategic planning (1)	Exploring opportunities (2)	PSS concept development (3)
Requirements (R)	C, I → R1 → O, M	R2	R3
Input (I)	Data from customer service, existing services, customer feedback and installed product base.	Principles of Theory of inventive problem solving (TRIZ), internal expertise on customer needs and wishes.	Consolidated list of requirementsand EC according to the function.
Constraint (C)	Restriction on collaboration in certain geographies or with uncertified suppliers.	Undocumented processes, lack of access and focus on functional aspects, contradictions.	Contradictions in requirements from all the stakeholders.
Output (O)	Internally generated needs and wishes of all the actors.	List of requirements and of measurable engineering characteristics (EC) from all actors.	Refined and verified list of functional requirements with no contradictions.
Mechanism (M)	Big data anaylsis, reports analysis, internal interviews.	Quality function deployment (QFD), contradiction matrix, TRIZ, Kano model, analytic hierarchy and network process (AHP and ANP), interviews.	Data envelopment analysis (DEA), requirement importance survey (likert scale).
Description (entities)	Systematisation of internal knowledge of actors' needs.	External requirement and EC elicitation and selection. Resolvement of contradictions.	Refinement and verification of requirements according to the function and the network.

Fig. 5. Requirements cluster mapped into ICOM notation in the three phases of early-stage PSS design.

infrastructure or the involved stakeholders (Alonso-Rasgado et al., 2004). To analyse such functions, Maussang et al. (2009) introduced interaction and adaptation functions that reflect the function provided by the product to the external environment and reactions or adaptations of the external environment, respectively.

All those functions ought to have a common goal of providing functionality that positively influences sustainability and forms a value proposition for the involved stakeholders (Rexfelt and Hiort Af Ornäs, 2009). Therefore, a functional unit (ISO 14040, 2006) definition is necessary for the early-stage PSS design, both to increase the range of potential design solutions that can fulfil the set function and to allow designers to compare the total environmental impacts of alternative PSS concepts per unit of functionality (Sakao and Neramballi, 2020).

The functions cluster and its constituent entities, elaborated using IDEF0 throughout the three phases of early-stage PSS design, can be seen in Fig. 6.

4.2.5. Offerings

The offering within the early-stage PSS design implies the main product and service components to realise the value proposition together with their interrelationships (tangible or intangible) (Alonso-Rasgado et al., 2004). It has a synonymous meaning with the PSS architecture (Shimomura et al., 2015) and it implies a much deeper inquiry into the composition of the offering than in a high-level consideration advocated in BMI.

Product and service elements and the modules they create together are the main components (i.e. the content) of the PSS offering as perceived by the customer, where the product can be observed as a vessel for service elements to be delivered (Aurich et al., 2006). A PSS module can be described as an integrated product and service with strong interdependencies among each other and different interfaces to the rest of the PSS concept (Song and Sakao, 2017).

The PSS content has to be distinguished from a channel or the delivery process to realise it (Sakao and Shimomura, 2007). As proposed by Ramaswamy (1996), the delivery process comprises the design of the service encounter environment, provider behaviour and customer-provider interaction. Since the delivery and the consumption of services is concurrent (Uno actu principle) (Becker et al., 2010), the delivery process should be meticulously planned to be able to deliver offering effectively and efficiently to beneficiaries (Alonso-Rasgado et al., 2004). The customer processes should be studied in-depth and should be reassessed with respect to what the customers think is their job in servicing the equipment (Hussain et al., 2012).

The offerings cluster and its constituent entities, elaborated using IDEF0 throughout the three phases of early-stage PSS design, can be seen in Fig. 7.

4.2.6. Structure

The PSS structure can be broken down into several building blocks: infrastructure, organisational structure, capabilities and the required resources.

	Strategic planning (1)	Exploring opportunities (2)	PSS concept development (3)
Function (F)	C, I → F1 → O, M	F2	F3
Input (I)	Existing functions, competitors' functions, functional requirements.	Data from installed base (e.g. mean time to failure), service tehnicians and customers. Function ideas.	A set of functions and their sub-functions.
Constraint (C)	No historical data.	Access to existing data not permitted (GDPR).	Regulatory, normative and cognitive. E.g. customer not willing to share the product.
Output (O)	Function ideas, e.g.: „to be available"., „to respond to an emergency"	Sub-functions: "to ensure smooth functioning", elaborated into: "to repair on-site within X hours by partner Y". FU e.g., "access to 10 km/day mobility for a month in Denmark".	Selected functions and FUs that satisfy as many requirements and have great potential impact and are easier to implement.
Mechanism (M)	Brainstorming, market research, mind maps.	Functional Analysis System Technique (FAST), why-how axis, QFD, functional block diagram (FBD).	Importance-performance analysis (IPA).
Description (entities)	Generation of possibly feasible functions from the ideas.	Decomposition into sub-functions. Co-definition of actors' functions and the FU).	TBL Evaluation and refinement of functions and FU across the life cycle.

Fig. 6. Function cluster mapped into ICOM notation in the three phases of early-stage PSS design.

The infrastructure or periphery includes all the support systems that enable the delivery of value of product and service modules through supporting equipment, software, facilities, tools, logistics, etc. (Shimomura et al., 2015). This support system operates in backstage and is not directly visible to the customer, but it directly increases the value of providers' assets and differentiates them from the competition (Müller et al., 2009). Consequently, the existing infrastructure may have a notable influence on the selection of the ultimate business model.

The organisational structure describes the organisation of the internal provider's stakeholders' interactions for fulfilling the beneficiary's needs (Trevisan and Brissaud, 2016). The definition of the organisational structure is important to generate cohesion and optimal operation of PSS and enable the successful servitisation of a company system (Morelli, 2006). Capabilities influence the PSS organisation, and if missing, they should be acquired externally, either through collaboration or the acquisition of external partners (Pawar et al., 2009).

The required resource implies all resources needed to realise any of the aforementioned constituent entities, and apart from the material resources, this category includes time, cost, human resources, the information needed from the installed base and current processes (Adrodegari et al., 2017).

The structure cluster and its constituent entities, elaborated using IDEF0 throughout the three phases of early-stage PSS design, can be seen in Fig. 8.

4.2.7. Plan for implementation

The final cluster entity to be conceived in early-stage PSS design is the implementation or realisation plan based on all previously described constituent entities of a PSS concept. The implementation plan is a roadmap with a timeline of required activities to realise the early-stage PSS design with assigned responsibilities of the actors in the network, including the contract drafting (Müller et al., 2009), the deployment plans (e.g. guidelines, checklists to be used by service staff) and staff training according to the necessary capabilities (Aurich et al., 2006). Existing PSS design approaches are short of such operational implementation planning guidelines in the industrial context (Andriankaja et al., 2016), but it is essential to account and plan for critical assumptions testing and validation of critical elements of the offering delivery to the market (Maussang et al., 2009). PSS is known for its implementation difficulty (Geng et al., 2010), therefore a systemised implementation and operation plan with the application of project management techniques to replace formerly intuitive activities is judged to be of substantial assistance (Aurich et al., 2006). The implementation plan is not often considered a part of early-stage PSS design, but within the complex PSS design domain, it is advisable to conceptually define such a plan in the early phases of PSS design because it can cause meaningful impacts in later stages (Rosa et al., 2021).

The plan for implementation cluster and its constituent entities, elaborated using IDEF0 throughout the three phases of early-stage PSS design, can be seen in Fig. 9.

4.3. A generic process model for early-stage PSS design

This section intends to target the third research question by devising a generic process model for early-stage PSS design (Fig. 10), which was built utilising the main findings and patterns observed concerning the

	Strategic planning (1)	Exploring opportunities (2)	PSS concept development (3)
Offerings (O)	C; I → O1 → O; M	O2	O3
Input (I)	Specifications and performance of existing product and services, internal and competitors'.	Value proposition, elicited requirements and functions. Historical product and service data from the installed base.	List of product and service elements, potential modules, and their functions.
Constraint (C)	No insight into exsiting product and service performance across their life cycles.	Prouct regulations and compliance issues. Technology unreadiness.	Incompatibilities of interfaces between products from different suppliers.
Output (O)	List of existing products and services in the market and their performance analysed.	List of potential products and services that can fulfill the function, and their potential module variants,	Hierarchized system structure, (sub-) elements with links and working principles. Defined service delivery process and its criticalities.
Mechanism (M)	Failure mode and effects analysis (FMEA), product life cycle analysis (LCA). Product and service KPI analysis.	Systematic creativity methods, problem solving techniques, morphological matrix, product and service design methodologies	Product-service relationship matrices, product service concept tree, Interpretive Structural Modeling (ISM)
Description (entities)	Identification and analysis of own and competitors' products and services.	Early definition of product and service clusters.	Total definition of the architecture and interaction between the entities of the offering.

Fig. 7. Offerings cluster mapped into ICOM notation in the three phases of early-stage PSS design.

workflows of activities, phases (Section 4.1) and gates (Fig. 11) to design them in the horizontal axis and the constituent clusters of entities (Section 4.2) in the vertical axis.

The three phases of the generic process model are separated by the decision-making gates demarked with lowercase letters a-d at each gate. Exclusively of the first gate, a decision based on the outputs of the previous phase must be made concerning the continuation of the PSS design project into the next phase. The notion of a highly formalised development process, where phases are delimited with gates (i.e. phase reviews) is regarded as having a positive influence on the efficiency of the development process (Holahan et al., 2014).

The process is envisioned to be used for different types of PSS innovations, namely radical, really new and incremental (Garcia and Calantone, 2002). The three innovation types have different scopes, and they focus on either a completely new PSS concept which embodies new technology and new market infrastructure (radical), a new concept in which technology or the market is changed (really new), or an incremental change of the existing PSS offering (e.g. optimising the service delivery process), respectively (Fig. 10). Therefore, the innovation type is a determinant factor for practitioners to select the starting point in the process model.

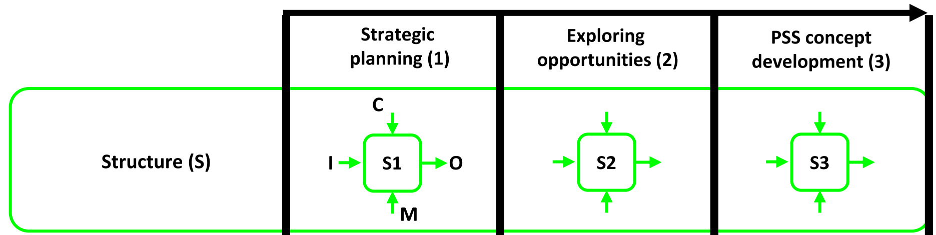
As this is a generic process model, which must be instantiated to company-specific context by the practitioners, no strict flow of actions is devised within each of the three phases, other than the chronological execution of the five activities (I. identification, II. analysis, III. definition, IV. selection, and V. refinement). Even though some focus should be given to all seven cluster entities in every phase of the generic process model (as indicated by trapezoids in Fig. 10), there are certain clusters of particular focus in every phase. Described phase by phase and separated by the gates, typical activities in the process model are described in Fig. 11.

Although the clusters are represented as independent modules, they are mutually interconnected and inseparable (Rosa et al., 2021) from other clusters within each phase of early-stage PSS design, as described in Fig. 11. The idea of the design process modularisation was introduced in the early days of PSS design (Aurich et al., 2006), where a process module is defined as a logically differentiable building block of a process, characterised by inputs and outputs with standard interfaces. Other authors successfully applied modular design thinking to trace the process of design through independent modules (Song and Sakao, 2017), where some process modules must be connected, and others conducted by complementing the corresponding inputs and outputs (Aurich et al., 2006), e.g. the outputs of the network cluster in phase one are inputs both to the phase two of the network and the business model clusters (see Supplementary material for more details about IDEF0 in the PSS development arena).

Therefore, the proposed generic process model contributes both to devising a meta-model, i.e. the structure of the process model itself (Becker et al., 2010), and the reference model which provides the necessary domain knowledge to be utilised in early-stage PSS design.

4.4. Sustainability considerations in early-stage PSS design

The generic process model for early-stage PSS design presented in Fig. 10 will not necessarily yield a sustainable offering unless such



	Strategic planning (1)	Exploring opportunities (2)	PSS concept development (3)
Input (I)	Current inventory of resources and capabilities.	Actors' network resources and capabilities. Internal infrastructure and capabilities.	Stakeholder's input about infrastructure and capabilities. Organisational structure and maturity.
Constraint (C)	No internal capabilities and/or resources.	Resistance to change and technology readiness.	New structure implementation time and difficulties.
Output (O)	List of existing infrastructure and capabilities for PSS implementation internally.	Organisation maturity for servitisation. Definition of the organisational structure (aftersales, field service, support, processing, account management)	Defined periphery (support equipment, tools, IT infrastrucure, facilities, movable assets)
Mechanism (M)	SWOT analysis, resource and capability analysis	Servitisation readiness assessment	Interviews and workshops with stakeholders.
Description (entities)	Exploration of the existing infrastructure that might inhibit or assist PSS design.	Definition the organisational aspects based on resources and capabilities.	Selection and refinement of the physical supporting infrastructure.

Fig. 8. Structure cluster mapped into ICOM notation in the three phases of early-stage PSS design.

considerations are thoughtfully made during the process. Many of the existing process models do not allow for such considerations and their exclusive attachment to any of the phases or constituent entities but are instead considered as vague transversal deliberations, therefore, it is uncertain what considerations to make and at what time. The generic process model proposed here is made fitting to sustainability considerations as it contains all the entities and a temporal perspective crucial for such considerations. In Fig. 12, the RQ4 is explicitly answered, as the relevant windows of opportunities to make different types of sustainability and circularity considerations and apply particular practices are indicated. Those considerations and practices can be applied throughout the three phases and are related to the seven clusters of entities. As in Fig. 10, no strict flow of considerations is devised due to the generic nature of the process model, which has to be instantiated to specific case applications and adapted to the context in which it will be used.

After receiving scarce initial attention from research, especially including the total TBL perspective (Kristensen and Remmen, 2019), PSS business model design has been recognised as much needed from a management perspective (Adrodegari et al., 2017) under the auspices of sustainable and circular BMI (Pieroni et al., 2019b) that represent a more strategic innovation at a business model level where the long-term potential must be balanced with short-term decisions (Panarotto et al., 2017). The key to circular or sustainable PSS BMI is to include the sustainability considerations and circular strategies (e.g. design for durability and take-back) into the value proposition design (Kristensen and Remmen, 2019) which will down the line guide the physical offering design. The design of a value proposition is a complex and unpredictable task in early-stage PSS design (Panarotto et al., 2017), but is a crucial piece as it is where the PSS offering's relationship to sustainability is primarily defined, while the offering (Section 4.2.5) is merely a way to deliver the value proposition. Therefore, sustainability and circularity have to be instilled in the value proposition and identified throughout the entire PSS life cycle (Nemoto et al., 2015).

The interconnection and collaboration of different stakeholders in an ecosystem are seen as crucial to innovation and change and one of the keys to designing TBL sustainable PSS (Chen, 2018). PSS can have a tremendous impact on the communities it operates in (Maxwell and Van der Vorst, 2003), and its success is in a great measure reliant on transparent long-term partnerships and customer loyalty (Moro et al., 2022).

Requirements have to be identified, analysed, and defined through all the life cycle phases (Song and Sakao, 2017) and all three dimensions of sustainability (Sousa-Zomer and Miguel, 2017). It is important to judge the value of the concept through the lens of both life cycle and sustainability dimensions (Nemoto et al., 2015) and also consider sustainability as a source of value (Kristensen and Remmen, 2019). To seize more value from sustainability endeavours, even a larger context behind the involved parties' needs (e.g. social issues such as labour right) should be recognised (Chen, 2018).

PSS's contribution to sustainability is bound to its functionality, as PSS has the potential to help decouple the volume of produced products from profitability by managing it based on functional value rather than materials content, hence reducing the impact on the environment (Wu et al., 2021). The functional requirements can cause many trade-offs between environmental and traditional considerations such as quality and cost (Pigosso and McAloone, 2016), and it is, therefore, pivotal to set the priority TBL performance indicators already in the strategic planning phase.

Environmental sustainability in traditional product development is a large body of knowledge, which has repeatedly proven the importance

	Strategic planning (1)	Exploring opportunities (2)	PSS concept development (3)
Plan for implementation (P)	C, I → P1 → O, M	P2	P3
Input (I)	Top management push towards the PSS design project.	Available resources and capabilities. Responsible individuals and initial project plan	Market reports and geopolitical situation. Project budget, timeframe and KPIs.
Constraint (C)	Lack of engagement and/or manpower.	Competitors plan to launch sooner.	Lauch timing and customer acessibility.
Output (O)	List of inividuals resposible for PSS development and execution internally. Chart initial project plan.	Project budget, timeframe and KPI definition for conceptual design and validation.	Plan and criticalities identification for embodiment and detailed design, and piloting (deployment). Roles and tasks definition.
Mechanism (M)	Strengths' assessment tools and motivational profiling tools	Project management tools.	Project management tools.
Description (entities)	Identification and analysis of internal project actors and their relationships.	Definition of a plan and KPIs for conceptual PSS design and validation.	Selection of internal actors and refinement of the implementation plan ahead of the go/no gate.

Fig. 9. Plan for implementation cluster mapped into ICOM notation in the three phases of early-stage PSS design.

of ecodesign and DfX (e.g. design for longevity) tools and principles to design more sustainable products throughout their life cycles (Pigosso et al., 2013).

The bulk of infrastructure consists of auxiliary products which can be designed using the same principles as with the main artefact. The design of a structure requires a long-term commitment and there is a real possibility that the lack of consideration of infrastructure, the provider's internal performance and coordination of capabilities and resources can erode a company's economic sustainability in the long run (Pezzotta et al., 2018). Even though the PSS has been stressed as one of the most effective instruments to enhance resource efficiency (Tukker, 2015), the identification of resource redundancies has not been addressed properly in the literature (Vasantha et al., 2015), and the allocation of available resources should be considered with great care (Shimomura et al., 2015).

4.5. Initial actions to implement the generic process model in a case study

The proposed generic process model serves as a reference starting point for manufacturers to tailor their designated process for early-stage PSS design, both in terms of the structure of the model itself and the necessary domain knowledge. It is considered that most practitioners (designers) will need to tackle the majority of entities and activities proposed in the generic process model to design a PSS from scratch, but some activities might be redundant depending on the stage of the company in their journey to adopt PSS. However, every practitioner should instantiate the generic process model to fit industry- and company-specific contexts, select the entities to address, and assign the exact flow of actions according to the company's readiness.

The instantiation process for the practitioners at a case manufacturing company with an established product design process, but not a PSS design process might include: (i) studying and comparing the terminology of the generic process model with the existing process; (ii) examining the contents of each of the three main phases and identifying new activities and entities ought to be included in the early-stage PSS design process as opposed to the existing product design process; (iii) identification of industry- and company-specific implications on the process (e.g. for a medical equipment manufacturer, the regulatory processes might need more attention both in terms of the business model and the network of actors); (iv) exploring the possible involvement of certain company departments and functions in the execution of individual activities to design all the required entities; (v) mapping of the newly introduced activities on top of the existing processes to comprehend the level of necessary changes to adopt; and (vi) embedding the instantiated process model in the daily work and acquiring the missing capabilities to design the needed entities.

After the instantiation, the company-specific process model for early-stage PSS design can be utilised for PSS design as well as further instantiated to specific PSS projects. It is envisioned that different parts of the organisation would contribute to conducting activities related to entities of their expertise (e.g., the legal department would take over the regulatory challenges in collaboration with other departments), while the whole PSS design project would be led by a PSS champion, i.e., the person managing the project and coordinating all the stakeholders.

The process of instantiation as well as the evaluation and refinement of the generic process model will be the subject of future research conducted through multiple case studies.

5. Discussion

The proposed generic process model considers the PSS design approaches from different backgrounds, namely engineering design,

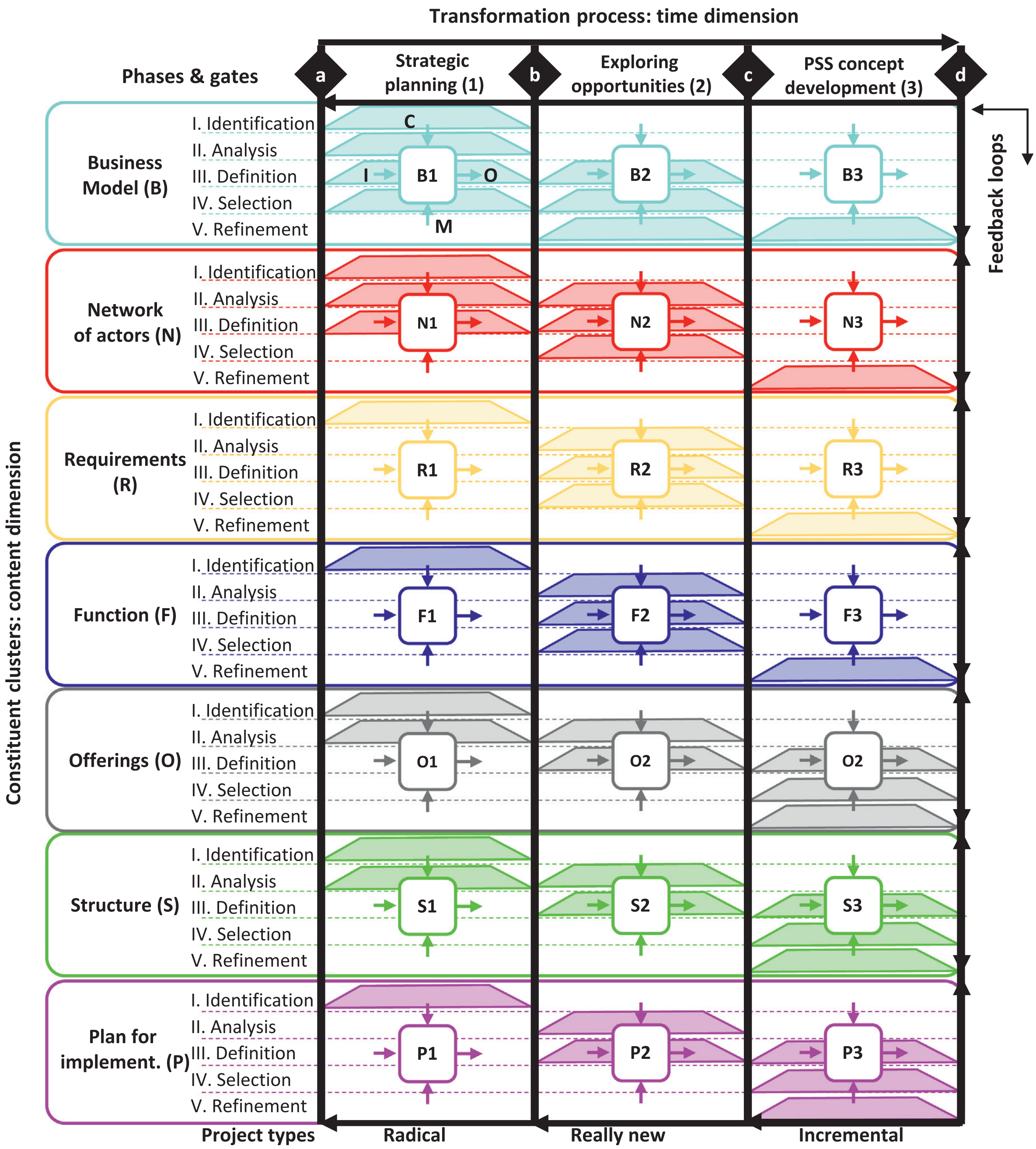


Fig. 10. A generic process model for early-stage PSS design. The activities where the focus must be directed in each phase (e.g. identification of the network of actors in the first phase) are accentuated with trapezoids, therefore devising a temporal sequence of actions for each of the clusters.

business management and information systems and provides a good basis to understand the connection between them by including the entities characteristic of each of the discourses, which was identified as lacking in the contemporary literature.

One could argue that business modelling approaches already include certain entities, e.g. key partners from the business model canvas (Osterwalder and Pigneur, 2009) might seem equivalent to the network entity identified here, however, the generic process model is focused on the delivery process of the PSS offering through the design of actor-networks as a much broader construct, and not merely their identification.

It could further be argued that the process of PSS design never fully comes to a stop, even when the dominant concept is reached, as the conceptual models are a (re-)construction of reality, but the reality evolves through time. Therefore, the concept should likewise evolve in the background when the offering with fixed architecture is operational in the market. This evolution of a concept can be triggered by an actor's feedback or changed requirements, internal innovations, or when the existing PSS offering has reached its end of use. Therefore, the project that started as a radical project and underwent the full process devised in the generic process model can be restarted via a feedback loop as an improvement project to incrementally ameliorate the concept. The different project types will primarily influence the source and type of input data in the process, varying from the existing customers and already operating product portfolio to new customers with a more exploratory approach. This is an especially important feature of the generic process model for practitioners who are new in the PSS offering market and are still exploring what business model should they operate.

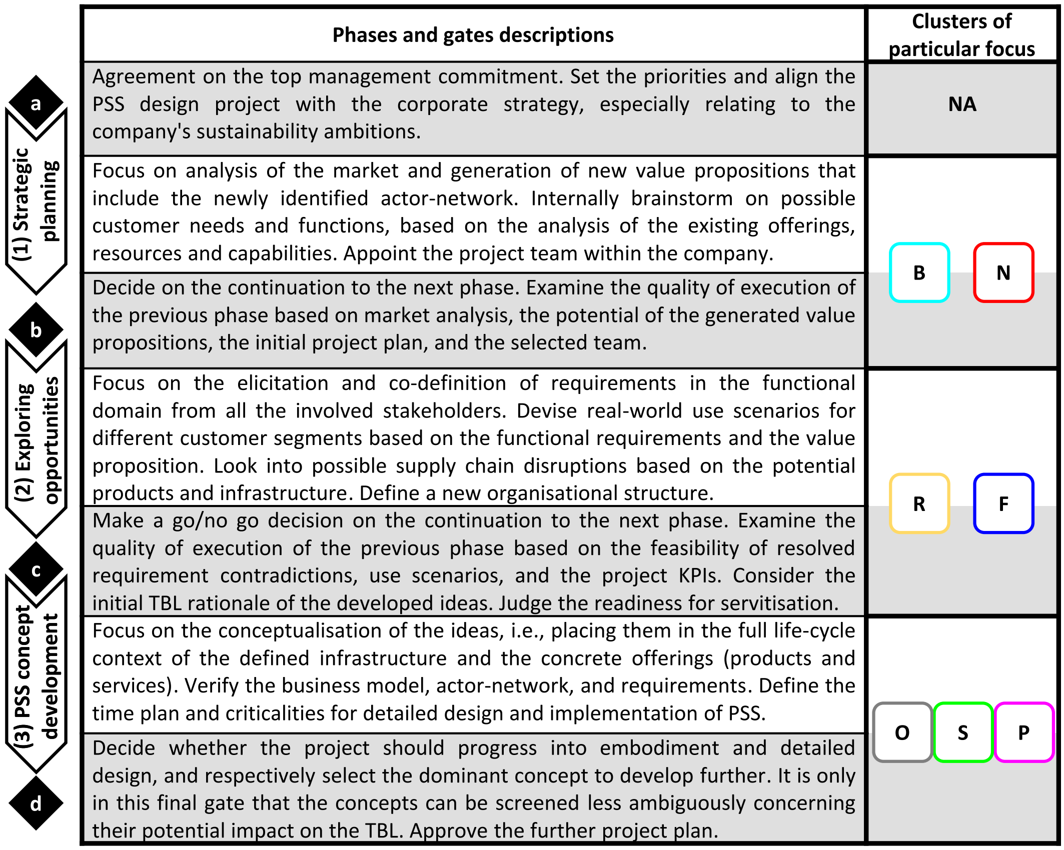


Fig. 11. The typical process of early-stage PSS design with elaborated phases and gates taking account of all the clusters of entities.

The generic process model is envisioned to be applicable for the design of all three PSS archetypes, product-, use-, and result-oriented (Tukker and Tischner, 2006), and in different business environments (business-to-consumer (B2C), business-to-business (B2B) or business-to-government (B2G)), which will be the subject of future research whether the model proposed here can be successfully applied to all the above-mentioned cases.

The entity clusters are represented as stand-alone modules despite their mutual interconnectedness and inseparability (described in Fig. 11). However, a modular process proposed here to reduce execution complexity is deemed a necessary trade-off for pragmatic utilisation in industrial companies without at the same time losing the essence of complex relationships.

Knowing that most approaches to early-stage PSS design are still intuitive and therefore ad-hoc in the industry, the modular input-output architecture of the generic process model split into different clusters enables easier model use by assigning different members of the design team to design certain entities concurrently and others sequentially, thus supporting a variety of readiness level for servitisation in terms of capabilities while also accelerating the design process.

The limitations of the proposed generic process model manifest primarily in its stage-gate structure, which hinders the necessity of cyclical and iterative early-stage design with many feedback loops (Fig. 10) in between the activities and constituent entities. However, the stage-gate structure is deemed necessary to enable more direct pragmatic application in industrial companies, as practitioners should arrive at a defined concept in a reasonable timeframe, without too many alterations to previous phases. For example, the network can be identified in the first phase of the generic process model but can only be selected once the function is selected so that the actors can be assigned to execute corresponding sub-functions. Therefore, even if the network and function selection both happen in the second phase, they do not necessarily happen fully concurrently. The gates, nevertheless, ensure practical progression and support decision-making throughout early-stage PSS development.

Both the feedback and the entity connection limitations are, however, a conscious trade-off in favour of industrial usability and for easier management of early-stage PSS design process which in most cases involves practitioners from various company departments and different backgrounds.

It has been found that very little consideration in the identified approaches was dedicated to sustainability considerations in early design, and even less to circularity considerations, although PSS represents a significant means to achieving a CE, due to its potential to provide decoupling of value creation from resource consumption. The generic process model narrows that gap by proposing the timing of relevant sustainability and circularity considerations in the early stages of the PSS design, where it is arguable that the considerations made at the earliest phases and concerning the upper clusters in Fig. 10 show more potential positive impact on sustainability, but also the uncertainties concerning the possible rebound effects. Further research inquiry must be dedicated to PSS circularity and sustainability evaluation, especially from the ex-ante perspective in the early stages of design which matters the most, where the constituent entities of early-stage PSS design that influence the TBL of sustainability first must be identified.

6. Conclusion

This article provides a comprehensive content analysis of the existing body of knowledge related to the early-stage design of sustainable PSS based on a systematic literature review. The accent is put on the definition of the phases of early-stage PSS design (strategic planning, exploring opportunities and PSS concept development), the constituent cluster entities of early-stage PSS design (business model, network of

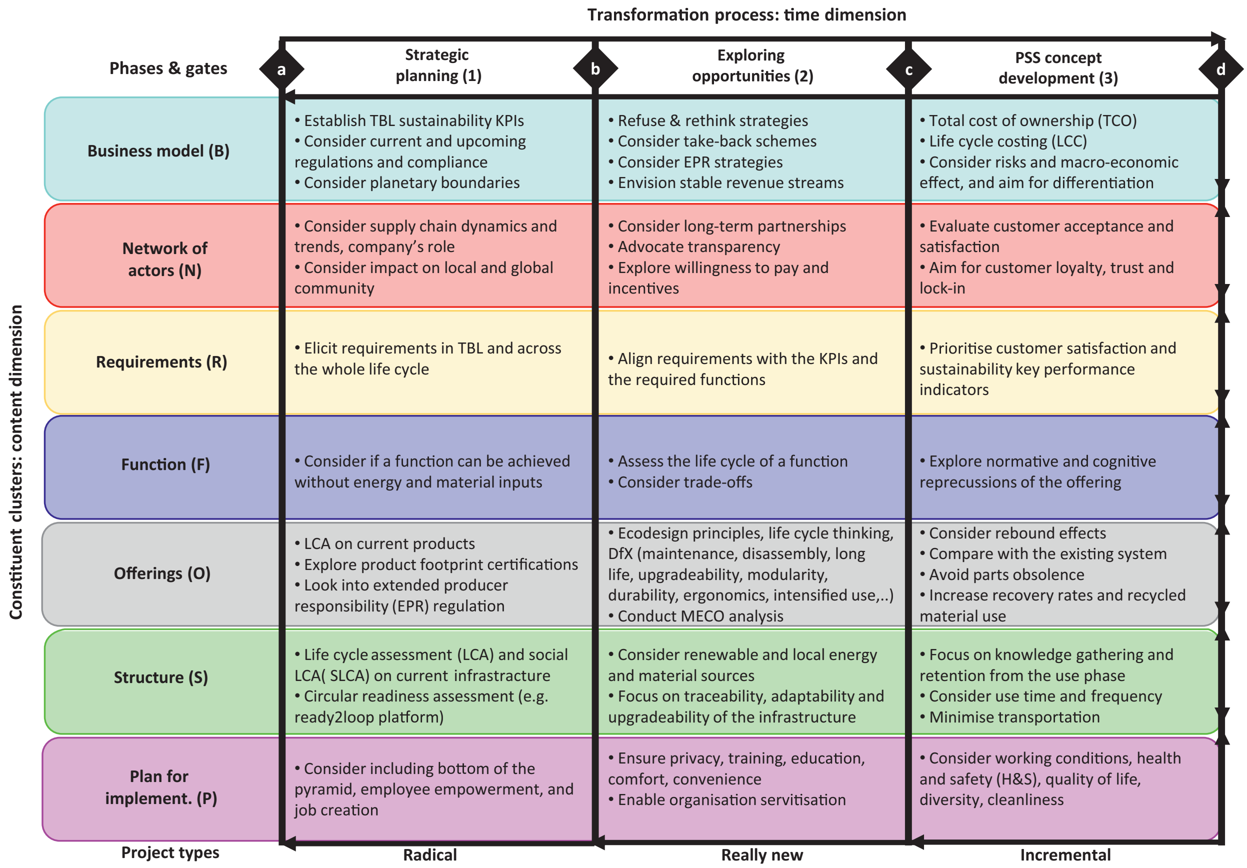


Fig. 12. Relevant sustainability considerations with respect to the seven entity clusters and in the three phases of early-stage PSS design.

actors, requirements, functions, offerings, structure and plan for implementation) as the outcome of early-stage PSS design, and the activities needed to devise each of the cluster entities (identification, analysis, definition, selection, and refinement). Building on the extant but focus-scattered state-of-the-art approaches for early-stage PSS design, the authors propose a much-needed and all-encompassing generic process model for early-stage PSS design in manufacturing companies, adaptive to diverse industrial needs. Due to the inherent inability of a design process to yield more sustainable concepts, this research further proposed relevant sustainability considerations to be made during the design process, mapped on the generic process model canvas according to the development phases and constituent cluster entities. Further research direction involves a more in-depth consideration of circularity and sustainability principles in the early design and evaluation of PSS concepts as well as validation of the proposed generic process in an industrial context. To increase the chances of the widespread general applicability of the proposed generic process model across the manufacturing sector, the authors propose multiple case studies with a recommendation to conduct them in companies of different sizes, different sectors, and with different PSS archetypes (product-, use- and result-oriented).

The main contributions of the paper are: (1) the analysis and characterisation of a comprehensive collection of PSS design approaches currently available in the literature using IDEF0; (2) the development of a generic process model for early-stage PSS design in manufacturing companies; and (3) the mapping of relevant sustainability considerations along the generic process model for early-stage PSS design. The process model proposes a generic approach based on the Rational Unified Process (RUP) characterised by the so much-needed adaptability to individual manufacturing companies, according to their needs in the early-stage design process of sustainable PSS.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

The Supplementary material includes (i) fully detailed descriptive literature findings; (ii) a complete list of the 96 selected approaches including their brief descriptions, focus clusters, backgrounds, and sustainability considerations; and (iii) a fully detailed description of IDEF0 in the PSS development arena. Supplementary data to this article can be found online at doi.org:10.1016/j.spc.2023.01.020.

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Appended publication 3

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Evaluation and instantiation of a generic process model for early-stage sustainable product-service system design within three manufacturing companies

David Sarancic*[1], Daniela C.A. Pigosso[1], Tim C. McAloone[1]

[1]Technical University of Denmark (DTU), Department of Civil and Mechanical Engineering, Nils Koppels Allé 404, 2800 Kgs. Lyngby, Denmark

*Corresponding author. (D. Sarancic)
E-mail address: dasar@dtu.dk

Abstract

Although product-service systems (PSS) have been in focus in literature and industry for some years, no generically agreed or applied PSS design process exists thus far, in contrast to the neighbouring fields of product development or service design, respectively. This paper presents the evaluation and instantiation of a recently proposed generic process model (GPM) for early-stage sustainable PSS design in capital goods manufacturing companies. The model was applied in three case studies with an aim to quantitatively and qualitatively evaluate the GPM concerning eight criteria, and study its instantiation process actions to a company-specific model while simultaneously identifying and proposing solutions for challenges to instantiation. Based on observation and feedback received from the companies, the GPM shows promise for widespread applicability, aided by proposed guidelines for instantiating the GPM to company-specific contexts, as also described in this paper. These guidelines aim to facilitate the translation of the GPM into pragmatic models for practitioners in the field of PSS design, thus increasing its chances of successful implementation as well as impact.

Keywords: product-service system; sustainability; servitisation; manufacturing; process model; case study

1. Introduction

Product-service systems (PSS) are offerings combining physical products and intangible services, supported by necessary infrastructure and networks, and designed to provide more value than traditional product-only offerings throughout the entire life cycle (Mont, 2004). PSS have gained increasing attention in recent years as a potential strategy for achieving sustainability, as they can have the capacity to reduce resource consumption and waste, and support the transition to a circular economy (CE) (Kjaer *et al.*, 2018; Lieder and Rashid, 2016), however, their real impact on sustainability is still debated (Roman *et al.*, 2023). CE is a model of production and consumption in which resources are used and reused in a closed loop, rather than being extracted, used, and discarded (Geissdoerfer *et al.*, 2017). Even though PSS can be seen as a way to move beyond the traditional linear model of production and consumption (McAloone and Pigosso, 2018; Pieroni *et al.*, 2018), it is important to note that PSS are not necessarily sustainable by default (Pigosso and McAloone, 2015), and the design of these systems must be carefully pondered, in order to achieve their full potential for triple bottom line (TBL) sustainability (Bech *et al.*, 2019; de Jesus Pacheco *et al.*, 2022; Sarancic *et al.*, 2022).

The design of PSS is a complex process that requires attentive consideration of many factors (Kimita *et al.*, 2022), including the concurrent product and service design, the needs and goals of the business and its customers, the business model, digitalisation, as well as the potential impacts of the system in operation (Kohtamäki *et al.*, 2021; Vezzoli *et al.*, 2015). Therefore, the expansion of the object of design both in its scope and heterogeneity is evident when compared to more established adjacent fields of product development and service design (Barravecchia *et al.*, 2020; Nemoto *et al.*, 2015). In the two fields, the complexity has to a large extent been harnessed and the process model supports have been well established (Olsson and Edvardsson, 1996; Ulrich *et al.*, 2020). However, the intersection of the two fields that PSS design represents invokes numerous challenges, but also opportunities, especially in relation to sustainability (Sousa-Zomer and Miguel, 2017). Early-stage PSS design culminating with a PSS concept is particularly important, as it sets the foundation for the entire system and can have a significant impact on its performance and success (Alonso-Rasgado *et al.*, 2004; Barravecchia *et al.*, 2020).

Nonetheless, even though companies are increasingly pledging to address the sustainability challenge by employing decoupling strategies such as PSS (Dhanda and Shrotryia, 2021), there is a lack of process models for sustainable PSS design in the existing literature to bridge the PSS field divergencies (Moro *et al.*, 2023), which can make it difficult for companies to effectively develop and implement these systems (Moro *et al.*, 2022; Sakao and Neramballi, 2020). Therefore, companies routinely rely on ad hoc and intuitive, rather than systematic approaches for the creation of PSS offerings (Bertoni *et al.*, 2019; Kim and Yoon, 2012). There are initial proposals in the literature to address this gap, the latest of which is a comprehensive generic process model (GPM) for early-stage sustainable PSS design developed based on a systematic literature review, completed by the authors (Sarancic, Pigosso, *et al.*, 2023).

Overall, PSS have the potential to support the transition to a CE and promote sustainable business practices, but their design must be thoughtfully considered in order to achieve these outcomes. The use of a structured and systematic approach, such as the GPM, can help companies to effectively and efficiently develop and implement PSS offerings that meet their TBL sustainability goals. However, the GPM must be instantiated to the contexts of specific companies. Therefore this study exposes the GPM to a rigorous evaluation process with three equipment manufacturing companies to ensure the applicability of a much-needed structured generic PSS design support (Brissaud *et al.*, 2022; Guillon *et al.*, 2021; Sakao and Neramballi, 2020). In this context, the following research questions (RQ) arose:

- RQ1: What is the usefulness and usability of the GPM within capital goods manufacturing companies?
- RQ2: How to enable the application of the GPM in practice to support PSS design in capital goods manufacturing companies?
    - RQ2.1: What are the actions the capital goods manufacturing companies took to instantiate the GPM to their specific contexts?
    - RQ2.2: What are the challenges the capital goods manufacturing companies encountered during the GPM instantiation?

To answer the RQs, this study aims to: (i) determine the model's level of adherence to a set of eight predefined criteria used to measure usefulness and usability, both quantitatively and qualitatively; (ii) observe and record the model's instantiation actions to create company-specific versions of the model in the companies; (iii) identify challenges during the instantiation actions; and (iv) propose guidelines for practitioners to optimally instantiate the GPM to company-specific process models based on the findings in (i), (ii), and (iii).

Instantiation implies the process of deconstructing and representing a complex generic process in a simplified or abstracted form, i.e., a process tailored to the specific context of a given company. This is typically done to decrease the complexity of the process, make it easier to understand, facilitate analysis and communication, and pinpoint significant elements of the model in a specific context (Polyvyanyy *et al.*, 2015). The goal is to configure the process so that it meets the requirements of the stakeholders and the context, while still retaining the essential elements and information necessary to comprehend the process.

2. Background

The GPM was developed for early-stage PSS design (Figure 1) based on a thorough, systematic analysis of the literature that included 96 pertinent PSS design approaches (Sarancic, Pigosso, *et al.*, 2023). To facilitate widespread adoption in industrial businesses, the GPM is aligned with a stage-gate form based on the Rational Unified Process (RUP) (Kruchten, 2000), and the functional modelling language IDEF0 (ISO 31320-1, 2012).

The GPM has the following components:

- A temporal dimension divided into three distinct stages (Strategic planning, Exploring opportunities, and PSS concept development) with four gates (a-d);
- A content dimension divided into seven clusters (business model, network of actors, requirements, functions, offerings, structure, and plan for implementation), each containing multiple entities (objects of design or consideration that can be grouped in a cluster) that can be designed using a workflow of five activities (identification, analysis, definition, selection, and refinement).

The structure of the GPM allows for the integration of sustainability considerations in every phase and entity cluster of the model, thereby increasing the likelihood of creating a more sustainable offering. The sustainability considerations to be pondered alongside the process model execution can be examined in detail in the original paper, where e.g., rebound effect consideration is prescribed in the Offerings cluster in the third phase.

The trapezoids in the model highlight the sequential order of activities and entities that require the most attention from manufacturing companies at each stage of the process, in order to develop PSS concepts. Each stage focuses on specific entities, as demonstrated by the number of trapezoids; for example, the business model and the network of actors are of particular importance in the first stage of Strategic planning. Although the clusters in the model may appear separate in the representation, they are interconnected in reality and multiple iterations and feedback loops are to be expected when using the process model. The gates serve as checkpoints, where decision-makers evaluate the quality of the previous stage and decide whether to move on to the next stage (Sarancic, Pigosso, *et al.*, 2023).

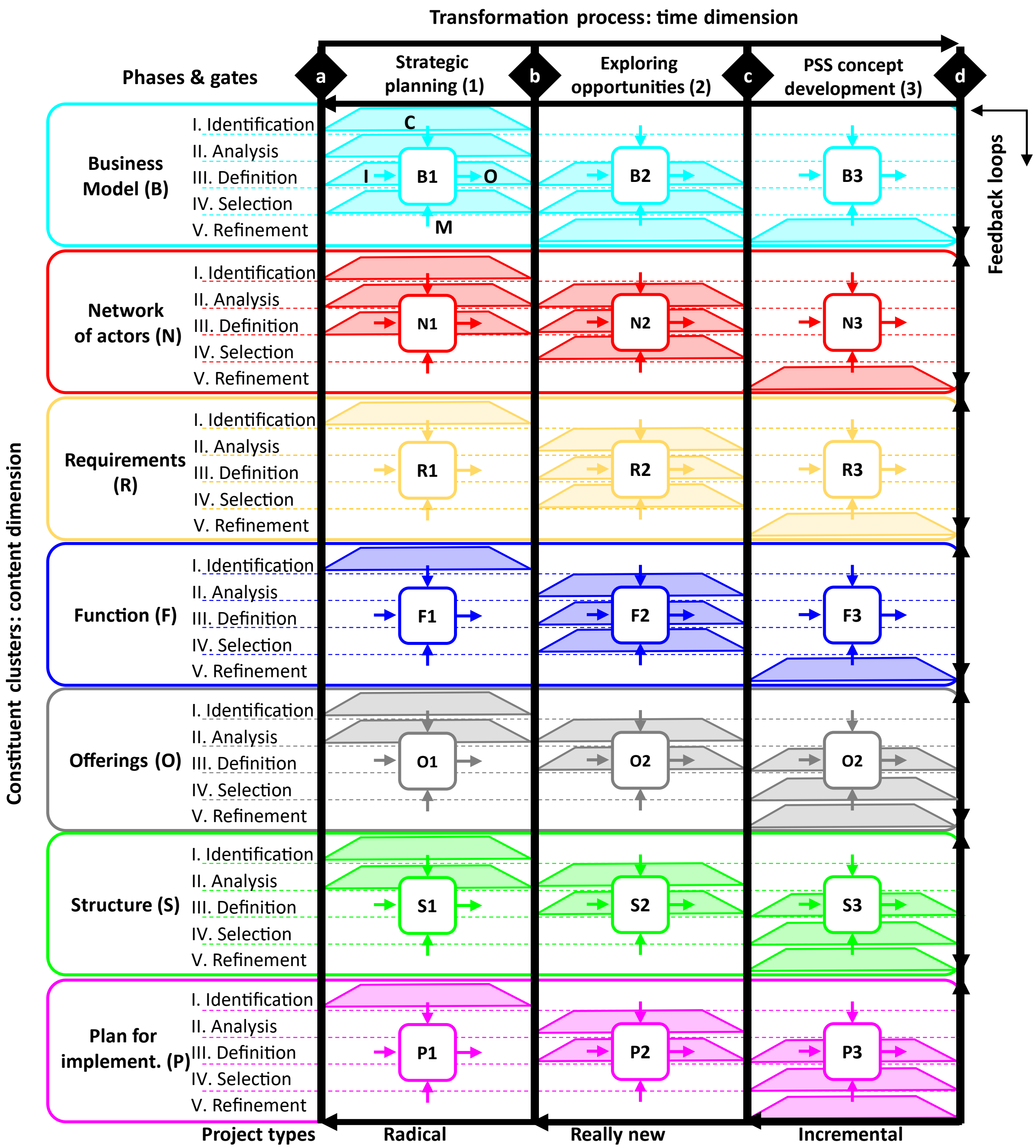


Figure 1. GPM for early-stage PSS design, adopted from (Sarancic, Pigosso, et al.*, 2023).*

3. Methodology

Seeking to answer the research question posed in Section 0, a hypothetico-deductive approach was utilised as a methodological framework (Gill and Johnson, 2002). Based on the objective of this study, which is to evaluate and enable widespread applicability of the rigorously theoretically developed GPM, a hypothesis was formulated regarding the research question:

- The GPM for early-stage sustainable PSS design can be instantiated to company-specific process models and support capital goods manufacturing companies to systematically and repeatedly design sustainable PSS offerings.

To test the validity of the hypothesis, a multiple case study approach was employed (Yin, 2003), which encompasses three Danish equipment manufacturing companies in dissimilar industries, including: food production machinery; medical equipment; and HVAC (heating, ventilation, and air conditioning) machinery, respectively (Table 1). The company representatives covered various functions and seniority levels (Table 1).

The selection of these companies was based on their (i) heterogeneous product offerings; (ii) diverse industries; (iii) dissimilar stages on their journey to adopt PSS offerings; and (iv) varying company sizes. This collection of characteristics was deemed necessary to span the largest spectrum of diversity of application of the GPM, in order to be able to bring forth sufficiently generalisable conclusions, despite the low sample size, regarding PSS design in the capital goods manufacturing industry.

The study was conducted over three overlapping six-month periods and the authors played a participative role in companies A and B, collaborating closely with the company representatives, as in action research (AR) approach, which enables collaboration of researchers and company practitioners to explore practical challenges (Coughlan and Coghlan, 2002). Companies A and B had no structured process for PSS design before this study and were only equipped with a process for product design. On the other hand, company (C) already had an established process for PSS design, therefore, direct participation was not employed in that case study. This provided a suitable diversity of perspectives and enabled a comprehensive evaluation of the GPM both in the environments unfamiliar with PSS and those that already offer PSS.

Table 1. Description of companies and company representatives involved.

		Company A		**Company B**		**Company C**	
Industry		Food production machinery		Medical equipment		HVAC machinery	
Type of business		B2B		B2B		B2B	
Headquarters location		Denmark		Denmark		Denmark	
Number of employees		350		2,000		42,000	
Yearly revenue		80 million €		270 million €		8 billion €	
Employee function	**Years of experience**	CTO	25	Head of systems	10	Standardisation manager	30
		Head of aftersales	20	Head of subscriptions	12	Sustainability manager	6
		Product manager	7	UX engineer	3	Senior design manager	15
		Sustainability manager	30	Innovation engineer	1	Head of digital service	25
		Technical support	25	Usability engineer	3		

An agile semi-structured approach was adopted for data gathering. Data collection methods included a series of meetings; semi-structured interviews; workshops coupled with observation and voice recordings that were transcribed for analysis; and finally surveys. Every representative listed in Table 1 was interviewed individually and while the representatives from companies A and B participated in workshops with the authors, company C held workshops without active author participation. The total interaction time is estimated at 8-12 hours per company, during which the qualitative and quantitative data were gathered and afterwards analysed using a combination of qualitative and quantitative methods (Yin, 2003). In the qualitative analysis, a specific focus was put on theme and pattern identification in the transcriptions of meetings, workshops, interviews and observations. In the quantitative analysis, the numeric judgments regarding the eight criteria on a Likert scale were examined to find the answer deviation and averages. The information that was gathered during the interactions and later analysed included GPM evaluation responses with respect to the eight predefined criteria, recordings of instantiation actions companies took and instantiation challenges, and general feedback serving as input to build the instantiation guidelines.

The eight predefined criteria are utility, consistency, completeness, scope, broadness, precision, simplicity, and clarity (adapted from (Pigosso, 2012; Vernadat, 1996) and further elaborated in Figure 3), which measure the GPM's usefulness and usability. These criteria were chosen due to their pertinence to the study's goal of creating a sustainable PSS design process model that is easy to comprehend and implement and were defined in an incipient evaluation study presented in Sarancic, Sánchez Díez, et al., (2023).

The findings of this study were utilised to create guidelines that will aid the instantiation of the GPM to company-specific process models, thus ensuring consistency and conformity with the specific requirements of the companies. The scale and the scope of instantiation characteristic of this study are depicted in Figure 2.

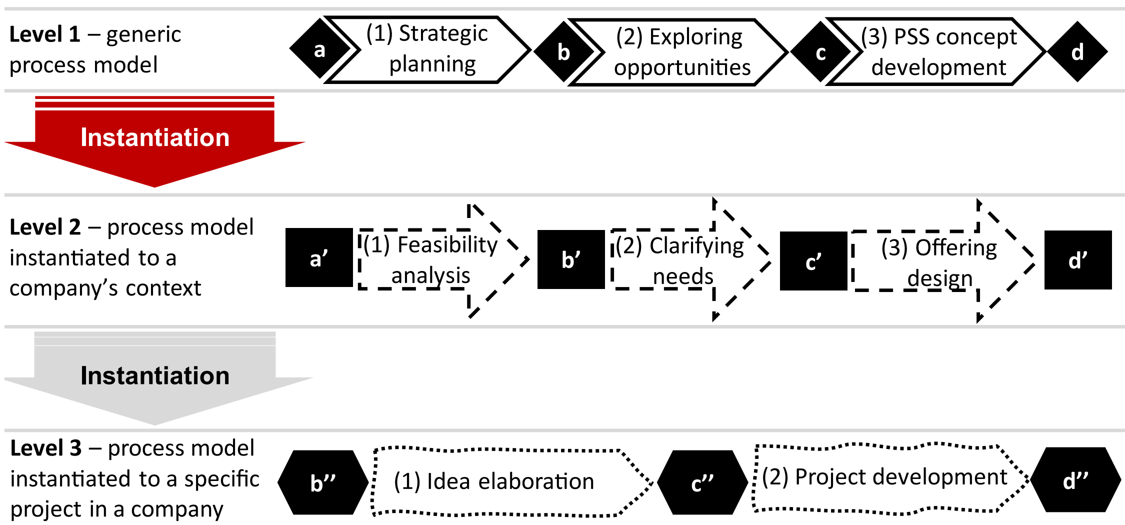


Figure 2. The scope of instantiation in this study is demarked with a red arrow. The figure shows that the instantiated process models do not require matching vocabularies, stages, gates, or contents, even though they use the GPM as a starting point.

4. Results

The result section is structured as follows: (i) Section 4.1 presents quantitative and qualitative feedback received from the companies in relation to the evaluation concerning the eight criteria (RQ1); (ii) Section 4.2 showcases the action steps companies took to instantiate the GPM to a version that fits their context (RQ2.1); (iii) Section 4.3 outlines the challenges companies encountered during their instantiation processes (RQ2.2); and (iv), Section 0 proposes guidelines for companies to optimally instantiate the GPM to company-specific versions (RQ2), based on the consolidated deliberations in (i), (ii), and (iii).

4.1. GPM evaluation

Figure 3 showcases the quantitative evaluation of the GPM conducted through a survey that followed the GPM application in the three companies, while Table 2 presents the consolidated qualitative evaluation obtained through the qualitative survey, interviews, and workshops regarding the eight criteria.

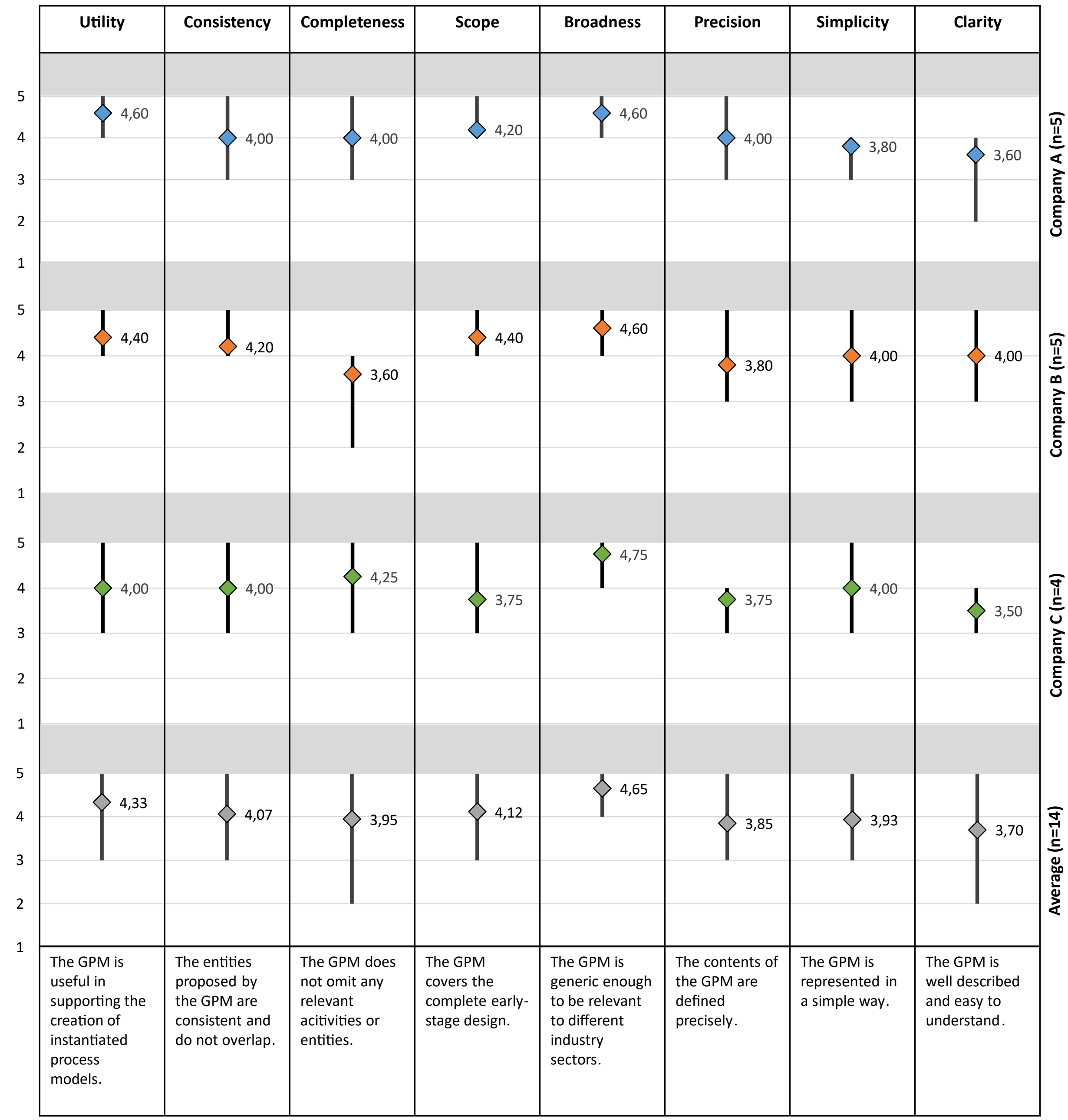


Figure 3. Quantitative evaluation of the GPM in three cases concerning the eight criteria. The four charts show average survey answers and the deviation ranges of the answers on a Likert scale of 1-5, where 1 indicates disagreement and 5 agreement with the sentences describing criteria below the graphs.

Table 2. Qualitative evaluation of the GPM in three cases concerning the eight criteria. Improvement opportunities are highlighted in italics.

Criteria	Company A	Company B	Company C
Utility	The model was judged of great help as a basis for the creation of the company's PSS design process model. Respondents considered that its usefulness mainly	The respondents found the model useful, singling out the benefits of a unified representation of all matters to be considered. Most of the	The model, even though comprehensive and knowledge-packed, *was considered difficult to apply without any guidelines that would simplify and*

	manifests in an all-encompassing overview of matters to consider and the activities to conduct.	stakeholders found the 360° approach practical, while *few stakeholders would have liked a more pragmatic clustering of entities that reflect the organisational structure.*	*accelerate its adaptation to company-specific purposes.* The model's modularity and the ability to use it partially were seen as its strongest points.
Consistency	An adequate degree of consistency was noted, although the *complex interconnections between the clusters necessitated occasional clarification regarding the specific entities (e.g., the difference between the network and structure cluster, which encompass external and internal actors, respectively)*	The users have not identified any inconsistencies. *However, getting familiar with the vast model and its entities required significant effort, especially when dealing with the newly introduced terminology specific to PSS.*	There were no overlaps observed between different entities. *However, it was challenging to gauge the consistency because many outputs serve as inputs into activities related to various clusters, therefore, yielding a perplexing input-output network where one cannot be sure which outputs were essential until the end of the process.*
Completeness	Although the respondents were pleased with the comprehensiveness of the GPM, *few entities might have gotten insufficient attention. More focus would have been preferred on investigating various technologies that could be used in PSS offerings. Another point was raised about putting a stronger emphasis on the creation of business cases for the generated concepts. Ultimately, a query was posed regarding the degree to which production and operation activities should be considered.*	Even though the GPM was seen as extensive, *it has been noted that it inadequately addresses regulations, compliance, and extended producer responsibility (EPR), which were considered crucial for the medical industry. Furthermore, one of the participants was concerned about the lack of pricing discussions under the business model cluster.* Many users noted their inexperience in PSS design projects and could not objectively evaluate the need for changes in entities or activities during the flow process.	The respondents were pleased with the totality of the model in the original paper*; however, they expressed that the sustainability considerations should be included in the main model, and not represented as a supplementary layer of the model.* This is because sustainability considerations are seen as an integral part of the business case in all new product and service developments in the company. *Also, a greater focus is needed on the installed product base and the data that could be gathered using IoT solutions, which could in turn enable more digital services.*
Scope	It was deemed appropriate to have three stages in the GPM with the scope including planning and conceptualisation as traditionally defined. *A point was raised about considering later stages of front-end innovation in the GPM (e.g., technology development). Another point was raised about activities usually occurring after the conceptualisation phases, namely, production planning and related operations.*	The support covers phases that align with those in Company B. However, the users are unsure if the entire process is correctly defined. While the scope of everyone's area of expertise appears relevant, *they could not assess the model as a whole, as they were eager to see how much easier the thoroughly generated outputs of GPM would make detailed product and service design in later stages*.	The respondents from company C agree that GPM thoroughly covers the early-stage PSS design. *However, they would prefer to merge the first two stages into one, as it would more closely reflect the existing stage-gate processes at the company*, and hence speed up the instantiation process afterwards.

Broadness	The GPM demonstrated a reasonable degree of flexibility. Although it was noted that *insufficient attention had been given to technology development and production,* the model could accommodate such considerations when instantiated, particularly within the structure cluster. Hence, it was considered applicable to other industry sectors.	The model was characterised as universal, therefore deemed malleable to any company. Nevertheless, being in the medical equipment industry, *the stakeholders felt insufficient attention was dedicated to incorporating regulatory and contractual matters.* But those fit under the requirements and network clusters when instantiated, respectively.	The respondents from company C represented different segments of a large organisation, each serving different industry sectors. They could not find a reason why would the model be better suited for use in any of the individual segments. Therefore, the GPM's broadness was marked highly, even when applied to projects with a more digital nature.
Precision	The cluster entities in the paper are mostly well-defined, except for technology development and production. *Respondents were slightly confused about the ecosystem's definition, which includes both internal structure and external network. Some terminology in the GPM was unfamiliar and needed clarification due to the unawareness of PSS vocabulary.*	Respondents agreed that the GPM's accuracy did not prevent effective usability. *Apart from unfamiliar terminology, the importance of the activities concerning each other was not clear.* One of the respondents drew parallels with similar entities in the business model canvas (e.g., partner identification) in contrast to GPM which additionally includes the definition of their roles and relationships).	The precision was defined as sufficient. *The respondents required more precision in terms of the timing of execution of different activities,* which they expected to be executed only once within each stage, rather than multiple times in multiple stages.
Simplicity	It is believed that early-stage PSS design, with all its complexities, cannot be presented more succinctly. *However, the instantiated process models stemming from the GPM may use simpler representations that align with the company's existing processes. Thus, omitting some of the characteristics of the GPM, such as IDEF0 constraints.*	This criterion received positive feedback, despite the complex and content-heavy model. *The users concurred that the GPM could benefit from interactive functionality to simplify it further and show only activities relevant to the user in question. The ranking of the activities in terms of their importance would make the model more actionable.*	Strong visualisation and succinct and simple input-output instructions in the IDEF0 and RUP notations were considered the model's strong points by the respondents.
Clarity	While the model may be easily comprehended at a superficial level, *understanding all its intricacies can be challenging, necessitating detailed accompanying explanations, and training before use.* Consequently, relying on the paper where the GPM was first proposed is deemed necessary.	The consensus is that the tool is comprehensive and well-structured, providing an excellent framework for decision-making. *However, some users recommended a more in-depth prior study of the support, introductory training on PSS concepts, and the addition of a timeline for the project flow to reduce its complexity and facilitate its use.*	*Further clustering of the existing clusters was proposed to additionally streamline the GPM. Fewer clusters with more content would be lighter in terms of between-the-cluster communication and reduce simultaneous considerations. Furthermore, the larger clusters should be precisely paired with specific tools (mechanisms) to be used.*

4.2. The instantiation processes

This section showcases the action steps the three companies took to instantiate the GPM to their contexts, (Figure 4).

Pragmatisation of the GPM characterised all three instantiation processes, where the larger the company, the stronger the push was exhibited towards model simplification, where even clustering of clusters and reduction of stages and gates was proposed by Company C. The reduction to essentials was deemed necessary to minimise chances of bottlenecks occurring in a perplexed organisational structure.

Despite the model simplification pattern, an elaboration level growth related to cross-departmental communication and transparency was observed in larger companies, which is a consequence of the larger number of involved stakeholders in the PSS design.

Mapping entities and activities in both directions from the generic to specific and vice versa was a habitual intuitive practice for all companies. Further commonalities were identified in terms of observations of all companies related to the importance of PSS-specific education (i.e., familiarisation with the PSS types, entities, terminology, and relationship to sustainability) before the instantiation of GPM.

GPM

	Company A	Company B	Company C
1.	Examine the terminology used in the current process model and compare it with the GPM.	Analysis of the company context and the motive to introduce PSS offerings for all the internal stakeholders.	Form a responsible sustainability working group that encompasses different functions and company segments. Align with the innovation teams.
2.	Compare the stages of both models, ensuring that the level of abstraction matches for future comparisons. Juxtapose their scope and content.	In-depth training about the PSS concept, the GPM, and its vocabulary before engaging in any other activities.	Organise an introductory training to clarify the terminology and relationship between PSS, CE and sustainability for the group.
3.	Identify individuals or departments (swimlanes) capable of handling different cluster entities and use organigrams to identify any other missing departments or personnel.	Identify differences between the existing process model and the GPM to uncover the magnitude of necessary changes in the organisation and activities that can be kept roughly the same.	Examine the model's contents. Merge the first two stages into one to eliminate excessive gate meetings and speed up the process.
4.	Map existing activities to the GPM to identify activities that are missing to create a complete instantiated early-stage PSS design process.	Extend the existing model (already structured in department swimlanes) with the newly discovered entities and activities necessary for PSS design.	Cluster some of the clusters further to get a more cohesive and simpler overview (e.g., requirements and functions).
5.	Identify industry- and company-specific entities and activities considered absent in the GPM (e.g., focus on production).	Identification of the dominant and critical path activities, as well as the criteria with respect to which those dominant activities could be prioritised.	Assign roles to all actors in the internal network participating in PSS design.
6.	Confirm with all relevant stakeholders that the mapping was conducted correctly.	Identification of the individuals responsible, accountable, supporting, and informed of a particular activity being executed.	Describe activities, inputs and outputs in detail given the interaction of the cross-functional team with other established teams. Introduce tool (mechanism) templates connected to every activity.
7.	Introduce milestones, deliverables, and key performance indicators that management can track and can easily be communicated between the stakeholders.	Map information flows between the stakeholders in terms of their content and timing to integrate the activities tighter.	Use workshops to eliminate repetition of activities that appear in multiple stages to avoid confusion returning to the same tasks (e.g., structure cluster definition in both stages 2 and 3 of the GPM).
8.	Establish activity and stage durations and deadlines appropriate for the company's context.	Retain as many existing processes and build on top of them to avoid unnecessary changes.	Define the special activities for different project types (radical, really new, incremental).
9.	Map the necessary organisational changes at the company level so that the instantiated process model can be embedded optimally.	Create multiple views of the process (e.g., top management or strategic view, PSS champion or project manager (tactical), and a view for each department (operational), to reduce complexity and avoid information overload.	Integrate the sustainability considerations in the same model as sustainability is an integral part of the business case in all new concepts and products they develop.
10.	Agree on the internal reporting and communication flows.	Clearly define deliverables, milestones, and decisions to be taken at the gates in detail to have a strong input for solid decision-making and to be able to judge the validity of the deliverable. Use checklists.	Pilot the process. If successful, integrate it as a formal part of the existing milestone plans.
11.		Define when exactly are communication sessions and feedback loops needed, between which stakeholders and about which entities.	Select a PSS champion to supervise the pilot. Set precise timelines, deliverables, and information flows given the pilot learnings.

Figure 4. Actions the three companies took to instantiate the GPM to their specific contexts. The icons indicate actions related to similar themes across the three companies.

4.3. Instantiation challenges

During the instantiation processes (action steps in Figure 4), companies encountered a number of challenges that slowed down or impaired the process. These challenges were consolidated and presented in Figure 5 after gathering the insights through observation and confirming them in interviews.

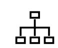
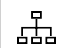
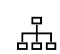
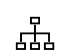
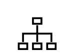
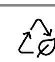
	Instantiation challenges	**Company**		
		A	**B**	**C**
1.	Getting used to the PSS-related terminology in the GPM and translating it to existing vocabulary in the companies.			
2.	The lack of resources to dedicate to this switch of paradigm. PSS might introduce unknown risks which are treated as non-necessary, especially in an already well-functioning company.			
3.	The willingness to change and consider new and different processes and organisational structure could be low due to rutted existing processes which always exist (even if not formalised).			
4.	Many of the GPM's activities were already present in the companies, however, with a narrower scope. Therefore, stakeholders used to execute them should expand their job descriptions and acquire new skills, or those skills should be acquired externally.			
5.	Mapping the information and communication flows (contents and timings) between the stakeholders, especially due to the iterativeness of PSS design activities can be challenging. E.g., requirements elicitation could stretch throughout the GPM due to a large ecosystem, where every actor has their requirements.			
6.	The challenge of fixing the sequence of the activities due to their cyclical nature, and the need to refine entities or e.g., define business model throughout multiple phases.			
7.	Lack of awareness of the connection and the impact of PSS on circularity and sustainability in a wider sense.			
8.	Selection and coordination of the right cross-function team in the instantiation might be challenging because different team compositions might steer the team towards different priorities.			
9.	The translation of entities and activities into the domain of responsible, accountable, supportive, and informed stakeholders can be challenging because of the multi-functionality required for some activities.			
10.	The inclusion of sustainability considerations directly into the instantiated model can further complicate the model.			
11.	GPM is a lengthy process, and it is difficult to judge if the project is going well before it reaches the end, especially since the objectives might change in the process.			
12.	The challenge of identifying dominant activities and prioritising them accordingly to be able to agree on standardised deliverables in every milestone.			
13.	Uncertainty in which activities and communication flows should the customers be involved and to what extent.			
14.	The practical issue of storing, sharing, and using the previous PSS project findings at the outset of new projects.			
15.	It might not be feasible to implement the new process in one go, but gradually, which might require a very long commitment from the management.			

Figure 5. Challenges companies encountered during the instantiation process. The icons indicate the connection of the challenges with themes identified in instantiation actions in Figure 4.

While analysing challenges, a great emphasis was placed on identifying critical activities and criteria to label them as critical, conceiving actionable standards for deliverables to be discussed at the milestone meetings, and establishing realistic timelines for project execution. A large amount of time dedicated to the formulation of decision-making instructions does not come as a surprise, as their suboptimal definitions lead to a lack of reliability in the results of the process (López-Mesa and Bylund, 2011).

A major hurdle in the instantiation for the companies, both in terms of time dedicated and complexity to be overcome, was the definition of communication flows between the departments (or individuals). Due to many entities and activities, coupled with the cyclical nature of PSS design imbued with feedback loops, it was deemed extremely important to clarify the potential communication bottlenecks. Furthermore, significant attention was focused on the allocation of roles and responsibilities, as well as defining the necessary capabilities to be acquired for the tasks not currently conducted in the companies (e.g., assessment of the existing infrastructure for PSS, partnership management, or product/service integration).

In the process of instantiation, organisational change was seen as a major barrier. Larger organisations would rather expand existing processes utilising the GPM or even introduce the instantiated process as parallel to the existing ones, rather than changing or replacing the established processes, to avoid all the changes that are not absolutely necessary, thereby reducing internal friction.

4.4. Instantiation guidelines

Based on all three companies' evaluations, actions steps and challenges encountered, consolidated instantiation guidelines for GPM instantiation in manufacturing companies were proposed (Figure 6).

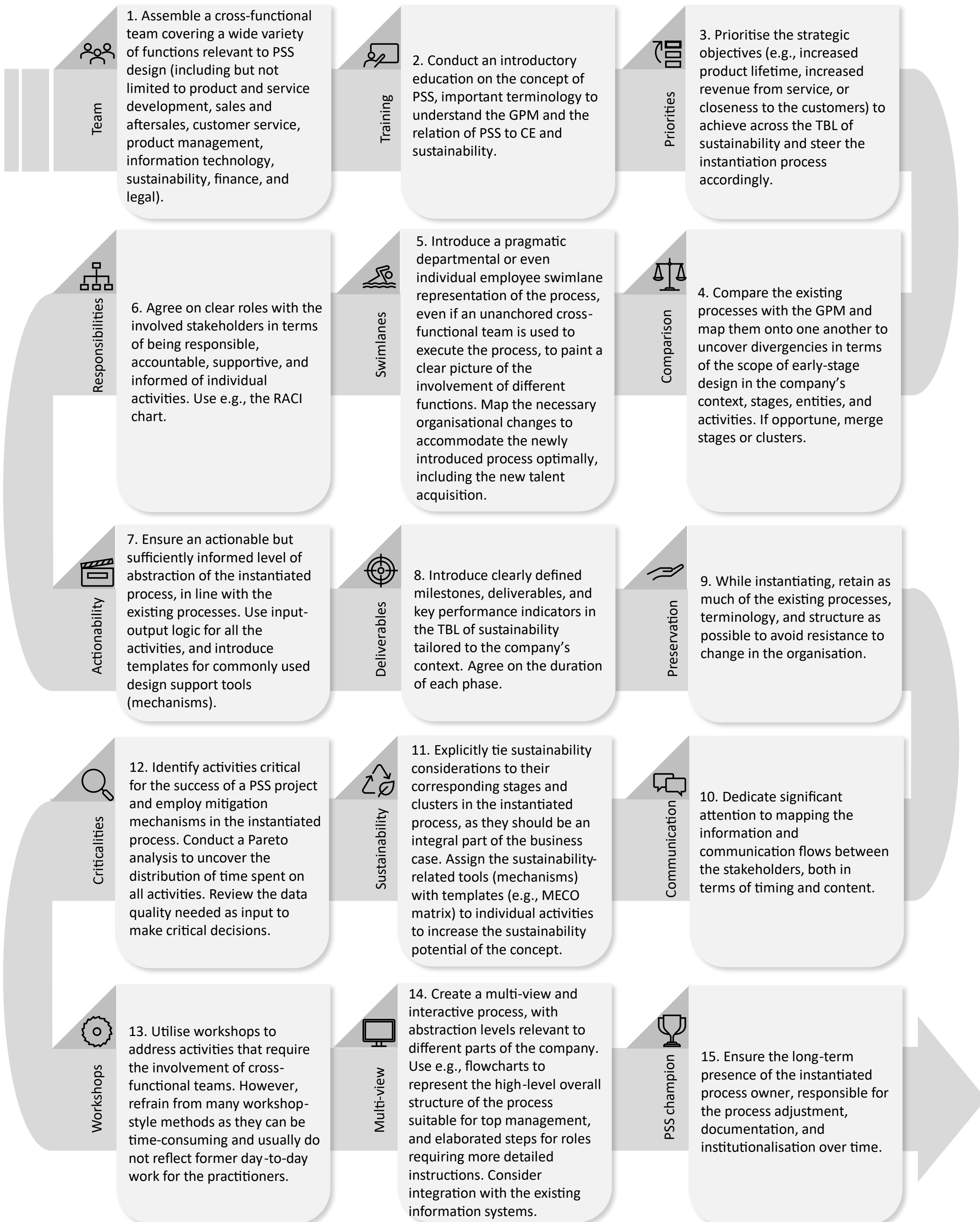


Figure 6. Consolidated instantiation guidelines for GPM instantiation in manufacturing companies. Each icon represents a theme, as identified in Figure 4 andFigure 5.

5. Discussion

This section serves to reflect and compare the empirically obtained results and state-of-the-art literature findings related to the evaluation of the GPM, instantiation actions, the accompanying challenges, and the consolidated instantiation guidelines.

5.1. On the evaluation of the GPM

The GPM was unanimously assessed as a useful starting point for the creation of company-specific process models for early-stage PSS design. While the GPM's all-encompassing perspective serves as a solid source of knowledge and structure to practitioners, the main objection to its utility is the lack of pragmatism in terms of being more specific to the individual company's needs. While this criticism is understandable from the perspective of an individual company's desire to have readily accessible support, it defeats the purpose of a widely applicable GPM that can be tailored to individual needs.

The authors acknowledge that customised process models for every company would have a paramount impact on boosting the large-scale adoption of PSS, however, due to the infinite number of contexts, it is considered a generic model such as the GPM, might be the optimal approach in terms of adoption speed of structured PSS design methods in industry since it can be tailored to, authors and respondents believe, most contexts. This tailoring process can now even be accelerated and conducted in a more structured way with the help of the consolidated instantiation guidelines proposed in this paper. These findings reflect the narrative in the literature, where some authors call for more precise approaches (Vasantha *et al.*, 2012), while others argue that might lead to even more limited implementability in practice (Tukker, 2015).

Despite being judged as complex, and occasional clarifications were needed, few inconsistencies were identified in the GPM. The clarification inquiries stemmed mostly from the lack of prior experience with PSS design and its terminology, rather than the shortcomings of the GPM. The precision criterion was, for the same reason, challenging to evaluate as it was difficult to distinguish imprecision from the respondents' lack of PSS-specific knowledge. Again, additional clarifications helped and were, therefore, purposely and preventively included in the consolidated guidelines in the form of prior education.

The model was deemed relatively complete and on the scope for the early-stage PSS design. Due to the nature of generic models, the completeness criterion was a subject of many discussions because every company will inevitably identify matters particular to their business (e.g., regulatory issues in medical business) and point them out as incompleteness. Therefore, even though authors strived to embed cross-industrial considerations identified in the systematic literature review that preceded the creation of the GPM, generic models cannot sensibly capture all intricacies of every context. One of the directions of future research might be to expose the GPM to a wide variety of contexts and further strengthen the coverage of industry-specific knowledge.

The GPM attempts to be sharply focused on early-stage PSS design, due to the pivotal importance of that stage. Therefore, although it is crucial to discuss the GPM's interface with front-end technology development and detailed PSS design happening chronologically before and after the timeframe that GPM adopts, respectively, those activities are considered out of the scope of early-stage PSS design. However, those points clearly indicate the need of having even more comprehensive process models that would include complete design, rather than just the early stages, which is the apparent future research avenue.

Although industrial companies have similar organisational structures, they are not identical, especially when taking small, medium and large companies into account. Therefore, it was considered more widely applicable to focus on the entities and activities that needed to be considered rather than prescribing which department should deal with those matters, because that would make the support less generic. Thus, it is left to individual companies to abstract the model to the degree and organisational context that suits them. In line with that, the broadness criterion was likewise positively rated.

Connected to the perceived lack of pragmatism pointed out concerning the utility criterion, the same discussion largely marked the evaluation concerning simplicity and clarity criteria. The respondents recognise that PSS design implies many cross-functional entities and activities, hence being inherently complex, but the common verdict was that such a compound process can hardly be represented more succinctly. Thus, multi-view (as in strategic, tactical, and operational views as proposed by Sarancic et al., (2021)) or interactive functionalities of instantiated versions were proposed as a remedy in which selective representations of the segments of the process relevant to the practitioner in question would be enabled. A practice like this would also make the instantiated processes less time-consuming, which is a common objection to their use by practitioners (López-Mesa and Bylund, 2011). It is deemed that all the intricacies of the GPM can be made understandable with appropriate prior training, which should put a strong emphasis on sustainability considerations as that was uncovered as underrepresented in the companies.

In the quantitative evaluation of the GPM (Figure 3), some criteria received marks with higher deviations around the average. These discordances in opinions were primarily related to completeness, clarity, and to a smaller extent, simplicity. The completeness discussion can to a large extent be attributed to the nature of generic models that purposefully focus on conveying information between the stakeholders rather than focusing on specific matters which respondents might consider important (Müller and Stark, 2010; Smirnov *et al.*, 2012). The simplicity and clarity criteria might be representative of the classic abstraction level mismatch between methods developed in academia versus industry (Beuren *et al.*, 2013), resulting in limited implementability and reluctance of industry to embrace new PSS design approaches (Baines *et al.*, 2007; Matschewsky *et al.*, 2015; Sassanelli *et al.*, 2019). It is considered that the consolidated guidelines proposed in this paper can help bridge the gap between the way that industry and academia are operating.

5.2. On the instantiation processes and its challenges

Many similarities naturally emerged between the companies' actions, therefore signifying the relevance of proposing consolidated guidance for instantiation that can be universally used.

Although there is little evidence to claim that one of the paths companies took to instantiate is better than the other, the actions that helped them create their instantiations and the challenges they encountered are deemed valuable to point out and share with future GPM instatiators. After all, process models assist not solely in providing systematic procedures to follow, but also assist the reasoning and decision-making done by the practitioners, which might be considered even more important in the high-uncertainty context that accompanies early-stage PSS design (Daalhuizen, 2014).

When comparing less (A and B) and more (C) experienced companies in PSS design, an obvious discrepancy presented itself in terms of the respondents' understanding of the instrumentality of the necessary changes in the organisation to switch from product to PSS offerings. Despite the prior knowledge and familiarity with the terminology, the relationship between PSS and sustainability was not clear in any company. Regardless of the multiple attempts to systemise the PSS design process internally in Company C, it remains incomplete. This may be caused by the character of PSS, which in a way represents the completeness of the company through an offering, meaning that the offering is a cumulative result of all the different entities and activities that constitute a company, and not only what was traditionally considered to be a part of the value chain in a manufacturing company. Therefore, what would be a single design process could be replaced by the company’s parallel evolvement of many functions, partnerships, and people to fully describe the PSS design process, as attempted in the GPM with several clusters of entities.

The main differences between the actions the three companies took manifested in industry-specific areas (e.g., medical and food safety regulations), and the internally routed flow of information and reporting.

The latter was different in every company, indicating that prescriptive claims regarding the responsibilities for individual activities in the GPM would have been futile. For that reason, the clusters of entities were adopted in the GPM, rather than departmental swimlanes, even though this conversion might be the hardest challenge for the practitioners instantiating the GPM. The process of instantiation onto departmental swimlanes is, therefore, recommended albeit noting that such arrangement of the workflows might hinder cross-collaboration unless communication flows are properly devised. Despite this possible disadvantage, the swimlane arrangement remains the most pragmatic way for the case companies to chart the process and roles.

Significant divergence was observed between the companies in terms of the accent placed on sustainability considerations. Sustainability-responsible respondents from the three companies had grossly different responsibilities and available resources, which corresponded with the company size. Smaller companies had more focus on economic sustainability, whereas larger ones petitioned to include environmental considerations as an integral part of the instantiated process. The companies which explicitly incorporated sustainability considerations in the instantiated process, therefore, moved a step closer to GPM's contribution to ensuring sustainable PSS. However, it has to be concluded that the sustainability of PSS concepts stemming from the GPM and its instantiated versions inherently relies on the motivations of the practitioners.

A concern has been raised regarding the impact that the selection of the stakeholders participating in the instantiation process might have on the outcome, i.e., the company-specific process model. While this issue might have some impact on the final result, especially if the company is at the beginning of the servitisation journey and does not even have a service department which should represent a significant weight in the instantiation process, it is considered that different team compositions should not impact the instantiation process to a great extent due to the GPM's robustness and comprehensiveness in elaborating all the relevant activities and entities. Furthermore, the exact purpose of the guidelines is to ensure that the instantiation can be done as objectively as possible by the practitioners without prior experience in instantiation or facilitation by experts.

The length and the uncertainty of the early-stage PSS design process can also present a challenge to companies, in the sense of not knowing the real impact of the PSS concept being developed until way in the future. The GPM, as well as empirical research conducted here, suggests a strong focus on establishing clear deliverables and key performance indicators to be assessed at milestone meetings. Moreover, the three stages proposed by the GPM should not be a binding constraint, and short sprint stages of quickly testing hypotheses (see e.g., (Ries, 2011)) may be better suited for some contexts.

The consolidated guidelines serve to support GPM instantiation and implementation of structured PSS design processes in manufacturing companies. When utilising the consolidated guidelines, practitioners will inevitably touch upon the many elements of servitisation, i.e., the organisational transformation companies need to go through to become service-oriented (Baines *et al.*, 2020). Therefore, the guidelines can be perceived as a bridge between structured PSS design and servitisation.

5.3. Limitations and future research

Despite being rigorously executed, this study is not without several limitations, the first being limited generalisability. Although the multiple case studies utilised in this research involved a diverse set of companies, the findings cannot be considered universally applicable. The second limitation stems from the possibility of bias and subjective judgments through observation, as commonly found in participatory studies. Further, multiple participatory case studies do not allow a high level of control over variables such as respondents' number and backgrounds, level of their collaboration, or types of interaction which tend to be agile and semi-structured. These factors can make it difficult to establish causal relationships between variables, and a more interpretative approach might be needed to analyse highly qualitative data.

Criticism could arise in relation to the evaluation of the instantiation guidelines, i.e., the lack of it. Notwithstanding their prescriptive nature, the guidelines could be considered evaluated throughout the instantiation process in the three companies despite lacking a formal evaluation study, as the participants judged the usefulness of each action before executing it in practice. Participants were, consequently, able to reflect on the challenges the action prompted. Therefore, only the already thought-through and useful actions were executed, which then contributed to devising the consolidated instantiation guidelines.

Apart from the future research directions mentioned in the above discussion text, which include further evaluation and instantiation of the GPM in more cases that satisfy the criteria listed in the methodology section, and expansion of the GPM to include complete rather than solely early-stage PSS design, there are a few other possible research directions for GPM's enhancement.

The GPM could be improved by introducing another layer that would tackle the information and communication flows between the clusters and involved stakeholders. Additionally, different versions of the GPM in terms of the most suitable mechanisms and sustainability considerations could be matched with the three project types the GPM tackles (radical, really new, and incremental). Furthermore, the GPM could be further detailed with respect to the degree of inclusion of digital technologies in the PSS offering, thereby following the PSS research development trend towards smart PSS.

Another possible research direction could be the rapid creation of business cases for PSS concepts, as that is a clear requirement from the industry, where the execution of the GPM could be deemed too lengthy for fast-paced industrial requirements, in times of disrupted supply chains when short delivery times matter more than comprehensive early-stage considerations.

6. Conclusion

A growing number of companies are pledging to address the sustainability challenge by utilising PSS, where increased value is provided through immaterial means, but few companies have adopted structured processes to deploy such offerings systematically and repeatedly in the market with good enough success rates. There are many approaches in the literature, but they are not adopted in industry due to their limited implementability.

The intention with this paper has been to provide a bridge between today's mostly intuitive nature of PSS design in industry, and hitherto disappointing PSS design approach adoption rate with the GPM for early-stage sustainable PSS design, which has been adopted, evaluated and instantiated empirically in three capital goods manufacturing companies.

The paper has: (i) presented a thorough quantitative and qualitative evaluation of the GPM concerning eight predefined criteria; (ii) reported the actions the three companies took to instantiate the GPM to the structures, systems, and language of their specific contexts; and (iii) highlighted both the applicability and the challenges encountered along the instantiation, to facilitate its uptake in industry.

Finally, consolidated guidelines for GPM instantiation in manufacturing companies have been presented, confirming the hypothesis that the GPM for early-stage sustainable PSS design can be instantiated to company-specific process models and support capital goods manufacturing companies to systematically and repeatedly design sustainable PSS offerings.

The guidelines are considered to support the industrial adoption of GPM, thus increasing the impact of this study both within academia and industry by boosting implementability and serving as valuable input for future development of more industrially implementable design supports in academia, respectively.

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Towards a novel Business, Environmental and Social Screening Tool for Product-Service Systems (BESST PSS) design

David Sarancic [a,*], Daniela C.A. Pigosso [a], Michele Colli [b], Tim C. McAloone [a]

[a] Technical University of Denmark (DTU), Department of Mechanical Engineering, Nils Koppels Allé 404, 2800 Kgs. Lyngby, Denmark
[b] FORCE Technology, Venlighedsvej 4, 2970 Hørsholm, Denmark

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A B S T R A C T

Product-Service Systems (PSS) have recently regained attention in the literature and industry due to their potential to contribute to sustainability. PSS are also enjoying renewed attention, currently, as the large societal focus on circular economy (CE) enforces the potential of PSS. However, PSS are not more sustainable than traditional offerings by default and they, therefore, must be designed with sustainability in mind from the early design stages and their sustainability potential screened already at a conceptual design stage. Existing approaches to screen PSS sustainability have conspicuous shortcomings regarding their lack of comprehensiveness, usability and focus on the conceptual design stage deemed crucial for the sustainability level of the future offering. There is poor coverage, in the literature, of approaches to sustainability-driven PSS design, and no consolidated approach to supporting a comprehensive consideration of sustainability aspects in the early stages of PSS conceptualisation. This paper introduces a qualitative tool and a process that support decision-making through ex-ante screening of PSS concepts for manufacturing companies based on the triple-bottom-line (TBL) sustainable value potential over the PSS life cycle. The tool was developed iteratively through three action research cycles focused on theory development and theory testing, within a manufacturing company. The tool and the implementation process are perceived as an effective and efficient way to screen PSS concepts through a comprehensive, yet readily applicable and usable approach by the industry practitioners.

1. Introduction

Never before has there been a stronger focus on both sustainability and servitisation in industry (Hallstedt et al., 2020). On one side, there is a rising trend among manufacturing companies to enhance revenue from through-life services (e.g. inspection, maintenance or repair) (Gebauer et al., 2010). On the other side, servitisation has the potential to decouple value creation from resource consumption, being a promising way forward for achieving sustainability (Kjaer et al., 2019). The implementation of service-based business models has the potential to extend the product life and reduce the need to manufacture new products, hence cutting costs and decreasing the environmental impact (Baines et al., 2007).

A service-based business model implies the development of more complex offerings, so-called product-service systems (PSS). PSS is a marketable combination of tangible products and intangible services (Goedkoop et al., 1999) that are life cycle oriented (Aurich et al., 2006) and supported by the infrastructure and the network of actors, designed to deliver more value than traditional transactional offerings (Mont, 2004).

PSS, a growing research field since the nineties (Tukker, 2015; Vandermerwe and Rada, 1988), is currently enjoying increased focus. The concept, nowadays popularly referred to as the "as-a-service" business model, has proliferated in recent literature, mostly due to advances in digital technology and circular economy (CE) (Pirola et al., 2020). Such business models are in close sync with recent policies in Europe, namely the Circular Economy Action Plan (European Commission, 2015) and the European Green Deal (European Commission, 2019) which emphasize their gravity in reaching the 2030 sustainability targets. CE aims to create the highest possible value and retain it for as long as possible while consuming fewer resources (Roy and Cheruvu, 2009), and PSS is seen as a possible key means of achieving that aim (Kjaer et al., 2018). PSS design is an integral part of service-related business development and there is a pressing call to support companies to integrate sustainability into their business development (Yang et al., 2017). Despite the intense development of tools and methods for PSS (Annarelli et al., 2016; Cavalieri and Pezzotta, 2012; Vezzoli et al., 2015), companies still face challenges when developing PSS (Pirola et al., 2020), especially in relation to sustainability (Qu et al., 2016).

* Corresponding author.
E-mail address: dasar@mek.dtu.dk (D. Sarancic).

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PSS is not by default more resource-efficient nor sustainable than the sole product (Bech et al., 2019; Tukker, 2015), and may lead to magnified environmental impact or decline in social interactions under certain circumstances (Doualle et al., 2015). Hence the revived original focus on contributing to sustainable development (Brundtland, 1987) through PSS (Kristensen and Remmen, 2019) can be seen in newer PSS definitions (Annarelli et al., 2016; Vezzoli et al., 2015) that include the sustainability triple-bottom-line (TBL) (Elkington, 1998), which is the most common framework to implement sustainability in businesses (Palmer and Flanagan, 2016) and the academic literature (Purvis et al., 2019). PSS has the power to achieve a "triple-win" situation concerning the TBL; through economic aspects (e.g., cost and profit); environmental aspects (e.g., energy efficiency and product longevity); and social aspects (e.g., customer acceptance) (Chiu et al., 2018).

Since none of those benefits is guaranteed (Tukker, 2015), PSS offerings ought to be screened as early as the conceptual design phase to reinforce the prospect of developing sustainable offerings (Maxwell and Van der Vorst, 2003). For that reason, this research aims to create a tool to address the lack of consideration of TBL when screening PSS concepts in the literature (López et al., 2020), in the early stages of design, and to answer the following research question:

- How to conduct sustainability screening of product-service system concepts in the early stages of design for the identification of triple-bottom-line benefit and cost hotspots?

To enhance clarity, the research question is further broken down into its specific elements:

- PSS concept: an actionable (implementable) and assessable (screenable) design proposal describing the total PSS solution including the system's composition, its functionalities and business model that fulfil the requirements of the involved actor-network.
- PSS concept screening: a simplified evaluation of alternative concepts to increase the likelihood of successful PSS development (Kim et al., 2013), which is more suited for the data-scarce early stage of design by its scope and level of detail.

2. Introductory literature review

The early-stage design is a crucial step in the development of sustainable PSS (Geum and Park, 2011; Sousa-Zomer and Miguel, 2017) and systematic early screening might avert resource allocation on design concepts with uncertain outlooks and risks of launching (Tran and Park, 2016). However, the early design phase is the most challenging phase, due to information scarcity and the inability to use data-intensive techniques (Rondini et al., 2020). Current methods have limited industrial applications; they are either too qualitative and unable to offer concrete concepts or too quantitative, which is expensive and time-intensive (Devanathan et al., 2010).

A common misconception in the PSS literature is that sustainability will be achieved if the designer follows the PSS design guidelines laid out, however, sustainability is not a given, when designing PSS (Tukker, 2015). Instead, a procedural sustainability screening is required to ensure that sustainability is designed into the PSS solution from the start (Maussang et al., 2009). Approaches to screen the sustainability of PSS are sparse in the literature, especially in the early design stages where it counts the most (Doualle et al., 2020). It is necessary to screen the sustainability of PSS as early as the conceptual design stage because most of the environmental, social and economic factors are determined in that stage (Bhamra et al., 2003), hence it is where truly effective impact can be made (Maxwell and Van der Vorst, 2003).

In the academic literature, PSS screening tools is one of the least addressed topics (Pirola et al., 2020). There is a significant concern regarding the scarcity of tools and processes to methodically screen alternative PSS concepts (Chen et al., 2015; Rondini et al., 2020), and to evaluate PSS performance both in terms of economic and environmental analyses (Annarelli et al., 2016; Tran and Park, 2016). Guiding principles to fully systematically screen the sustainability of a PSS are even scarcer in literature (López et al., 2020). Furthermore, there is a lack of support on how to design, develop and screen new value propositions, which are both more service-oriented and sustainable in all TBL dimensions (Qu et al., 2016).

Despite the current literature gaps, existing state-of-the-art tools and methods related to PSS screening were identified through a separate literature review and thoroughly analysed as a part of this research (Section 4.1), as explained in the Methodology. Furthermore, as presented in Section 4.2, an additional literature review was conducted to elaborate on the key dimensions to consider when screening PSS concepts.

3. Methodology

The research steps were carried out iteratively through a hypothetico-deductive approach (Gill and Johnson, 2002), by combining theory building and theory testing. The development and test of the proposed tool were carried out in the context of action research (AR) (Coughlan and Coghlan, 2002) in collaboration with a manufacturing company in the capital goods industry.

AR was deemed appropriate as it was a useful method to verify the early stages of research and test theories (Dyer and Wilkins, 1991). This particular company was selected because it is considered typical of many other manufacturing companies in the capital goods manufacturing industry (Sarancic et al., 2021). It is furthermore selected because the authors had a unique opportunity to observe and analyse the phenomenon previously rarely accessible to scientific investigation and interact directly and continuously with responsible decision-makers as a part of the ongoing research project.

Despite the high level of practical relevance and the possibility to gain in-depth insights into the problem, there are certain threats to the validity of AR. Namely, the lack of impartiality of the researcher and the danger of being considered a consultant (Coughlan and Coghlan, 2002). These drawbacks are tackled by also utilising theoretical rather than solely empirical justification and with rigorous documentation in a cyclical fashion, unlike in linear consulting practices.

The research was structured in three cycles according to the four main steps of AR: diagnosing, planning action, taking action and evaluating action (Coughlan and Coghlan, 2002) (Fig. 1). AR is a participatory research method that involves taking action concurrently with knowledge creation and has been successfully used in PSS design (Tonelli et al., 2009).

3.1. Context and purpose

The empirical setting for the AR was a Danish mid-size machinery manufacturing company. At the time of the study (July 2021 to March 2022), the manufacturing company was in the early stages of PSS development as a means of contributing to the newly adopted TBL-oriented strategy. The company expressed the need to systematically select the PSS concept with the highest sustainability potential for further development, as they had very limited previous experience with PSS, and had only reactively and intuitively developed a few product-oriented PSS offerings.

A literature review of existing tools for PSS sustainability screening was conducted to identify potential tools to be used by the company. The search was conducted in the Scopus database by combining the synonyms of the keywords "product-service system", "sustainability" and "screening" and nine relevant tools were identified. The obtained tools were evaluated through collaborative quantitative data analysis (Miles and Huberman, 1994) together with the company representatives, resulting in the identification of a lack of existing tools suitable

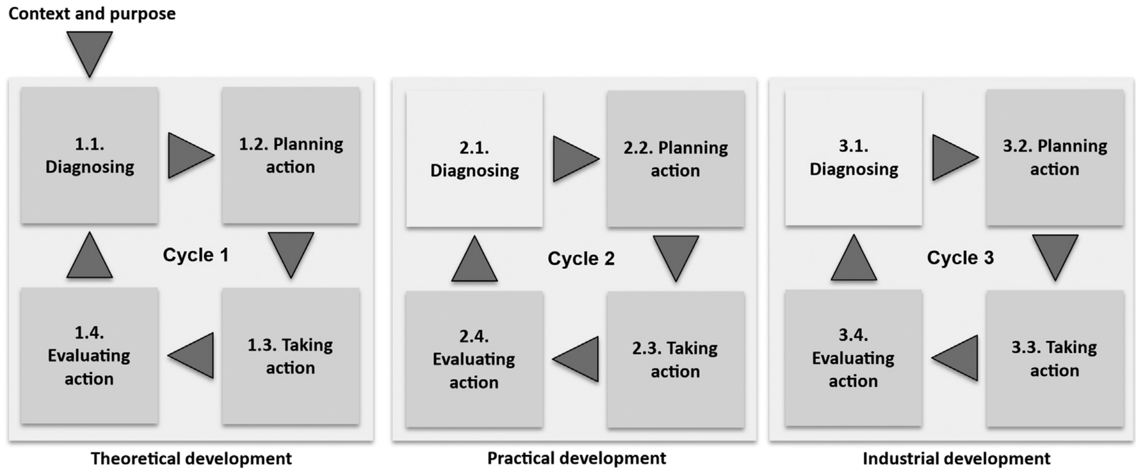


Fig. 1. Research approach cycles.

to support manufacturers in the early-stage sustainability screening of PSS concepts.

3.2. Cycle 1: theoretical development

1.1. Diagnosing. Empirical research, i.e. 10 hour-long semi-structured exploratory interviews (Robson and McCartan, 2016) were conducted with seven case company managers. The interviewees were covering diverse functions (chief technology officer (CTO), aftersales, sales, corporate social responsibility (CSR) and sustainability managers) and seniority levels, ranging from three to 20 years of experience in managerial positions. The selection of interviewees was based on a strategic and purposive sampling strategy (Karlsson, 2008), covering diverse functions and seniority levels. The interviews aimed to identify the success criteria for the development of the PSS sustainability screening tool, informed by the previously conducted collaborative analysis of the existing tools in the literature. Therefore, the interviews revolved around the following question: "What success criteria should the tool for PSS concept screening satisfy?". The gathered data were consolidated, giving rise to the empirical success criteria for the PSS screening tool and eliciting the need to further explore the key dimensions for the screening of alternative PSS concepts (i.e., the TBL, life cycle thinking, value and PSS elements).

1.2. Planning action. An additional literature review to uncover the relation between PSS and the identified dimensions for PSS sustainability screening (step 1.1.) was conducted for theory building. Four separate searches were conducted in Scopus by combining the synonyms of keywords "product-service system" and the four dimensions. The gathered data were qualitatively analysed together with the company representatives to uncover the complex relation of PSS and the key dimensions identified for its screening. The analysis included the evaluation of the detail level that the decision support tool should be able to provide, concerning the elicited success criteria. This step also covered the planning of the development (1.3.) and the evaluation (1.4.) steps in this AR cycle.

1.3. Taking action. The first version of the tool was developed based on the combination of the review of existing tools, the empirically elicited success criteria, and the identified key dimensions through a series of workshops and meetings with the relevant stakeholders. The interactions focused on the development of the content and the logic of the tool while ensuring conformity with all the elicited success criteria and the key dimensions obtained (step 1.2). This step consisted of four workshops and two follow-up meetings with the company representatives. The first version of the decision-making tool was built iteratively by following the elicited success criteria, starting from the overarching strategic aspects and then progressing towards more operational aspects.

1.4. Evaluating action. The first version of the tool was tested through three two-hour-long workshops. The first workshop was focused on the evaluation of the logic of the tool and was supplemented by the second workshop (with two external industrial experts in service innovation). The third workshop (conducted between the authors and external experts) was focused on evaluating the tool's user interface and functionality. Improvement opportunities were identified both in the logic and user-friendliness of the tool through the application of the tool to different PSS concepts. A thorough re-alignment of the definition of the key dimensions and their inter-relation was the main outcome of this step.

3.3. Cycle 2: practical development

2.1. Diagnosing: N/A

2.2. Planning action. The planning of the second AR cycle included a series of meetings for the development of the second version of the tool, based on the identified improvement opportunities in the first cycle. Furthermore, this cycle involved the planning for the further test of the tool with master students, to enable broader applicability in different contexts.

2.3. Taking action. The second version of the tool was built based on the evaluation described in step 1.4. The contents and the logic of the tool were further detailed, leading to a consensus on the definition of the key dimensions. This was done through meetings between the authors, followed by a meeting with the company representatives. In this step, a visual representation of the concept screening tool was devised, as the case company found it crucial to be able to easily communicate and compare alternative concepts. Then, four distinct implementation processes were devised to make the implementation process simpler and quicker to use.

2.4. Evaluating action. The second version of the tool was tested in a workshop with 17 students, in four randomly formed groups of 4–5 students, attending a PSS master-level course at the Technical University of Denmark. The evaluation focused on the tool's user interface and functionality. A dominant tool implementation process emerged in terms of the sequence of steps that enable the greatest simplicity and agility. To retrieve qualitative empirical data and ensure the validity of the student feedback, interviewing, direct participation and observation (Robson and McCartan, 2016) were used during the workshop. A feedback survey was conducted after the workshop in which students rated the feasibility, usability, and utility of the tool.

3.4. Cycle 3: industrial development

3.1. Diagnosis: N/A**3.2. Planning action.** The planning of the third AR cycle included the development of the third version of the tool and the planning of the evaluation workshops with the case company.

3.3. Taking action. The third version of the tool was built to include the considerations step 2.4, i.e., the incorporation and detailing of the implementation process. The development was conducted through two meetings between the authors, followed by a meeting with the company representatives, where the implementation process was streamlined and presented to the company. The outcome of this step was a tool ready to be used with the case company.

3.4. Evaluating action. The third version of the tool was tested in the case company in two separate workshops, lasting 2 and 3 h, respectively. The workshops were facilitated by the authors and included previously interviewed managers from the case company. In these workshops, primarily success criteria related to the functionality of the tool were tested (i.e., whether the tool can support decision-making regarding concept screening and selection).

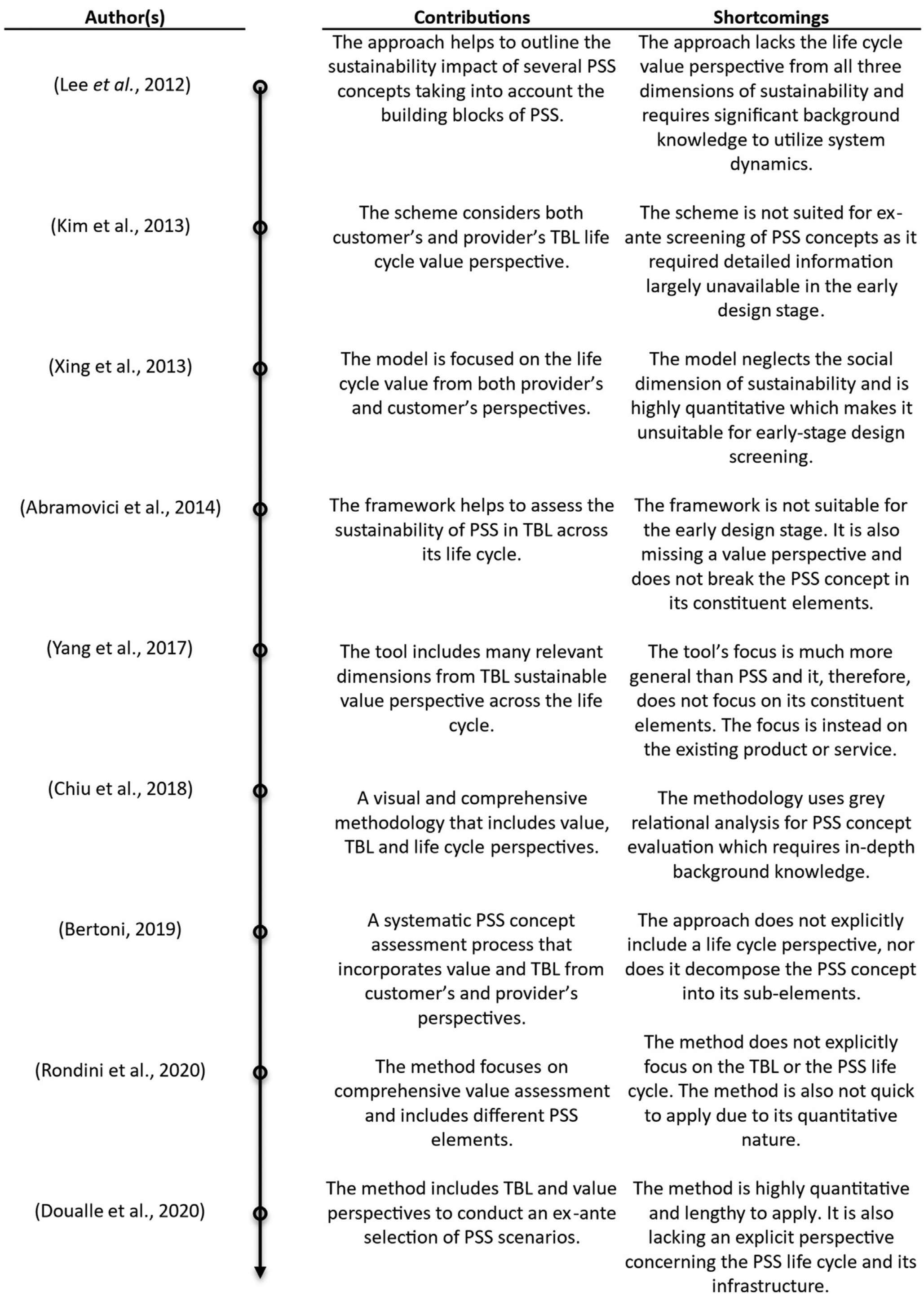


Fig. 2. Selected approaches that emerged from the literature review.

4. Results

4.1. Context and purpose: review and analysis of tools and methods

Despite being one of the least addressed PSS-related topics (Pirola et al., 2020), nine approaches (Fig. 2) were identified in the literature that serve as a knowledge base for the development of the novel approach presented in this paper. None of these approaches explicitly answer the research question but each makes a specific contribution to the understanding of either PSS concept screening or PSS sustainability screening. The authors acknowledge numerous other approaches for PSS concept screening present in literature (see e.g. (Bertoni et al., 2018; Montelisciani et al., 2015; Sakao and Lindahl, 2012; Song et al., 2021)), however, these nine particular approaches were selected because they intentionally prioritise two or all three dimensions of sustainability in the most comprehensive way. The nine approaches identified in the literature tackle PSS screening from various perspectives, and they were thoroughly analysed to capture their contributions and shortcomings, thus paving the way for the development of an approach that is comprehensive, usable and focused on the conceptual design stage screening.

The existing screening approaches (Fig. 2) are disparate in their scope and the dimensions that they propose to be included, in the sustainability screening of a PSS concept. Due to the identified shortcomings in those approaches, none of the listed approaches was deemed appropriate for use – on their own – for PSS sustainability screening, as was also confirmed in the setting of the empirical case company, by the committee consisting of authors and case company representatives. Therefore, a PSS sustainability screening tool that would unify the most important contributions and overcome the shortcomings of the existing approaches (Fig. 2), with a clear focus on early-stage concepts and a straightforward implementation process, was deemed necessary.

4.2. Cycle 1: theoretical development

4.2.1. Step 1.1: Success criteria for the development of the tool

The main outcome of this cycle was the identification and consolidation of the success criteria for the development of the sustainability screening of PSS concepts (Fig. 3).

4.2.2. Step 1.2. Reviews and analyses of the key dimensions

In the following subsections, the findings from the literature reviews on key PSS dimensions (i.e., PSS elements, the TBL of sustainability, value and the PSS life cycle) are outlined.

4.2.2.1. PSS elements. Despite the wealth of publications in the field, the PSS literature has not yet reached a standardised definition of the structural architecture of PSS, i.e., the constituent elements of the PSS concept that have to be designed to deliver the value proposition (Tukker, 2015). To be able to define the structure of a PSS concept, a literature review of PSS definitions was carried out to identify the PSS building blocks (Fig. 4).

The most recurrent elements in the PSS definitions are products, services, network and infrastructure. Although most authors agree that PSS can be split into products and services, fewer include network and infrastructure as core elements. Tonelli et al. (2009) argue that PSS is strongly context-related and to evaluate it means to analyse the internal and external ecosystems of a company. Therefore, collaboration with the involved stakeholders from the early stages of PSS design all the way through PSS operation is crucial for the development of steadfast and long-lasting customer relationships through PSS offerings (Fernandes et al., 2020). The infrastructure enables value delivery through supporting facilities, logistics, tools, soft and hard products, etc., which directly increase the value of the PSS provider's assets (Xing et al., 2013) and differentiate the provider from the competition.

This analysis was substantiated by examining the characteristics of PSS definitions with the highest citation index (Haase et al., 2017), where the most recurrent PSS characteristics were found to be product and service, customer needs, network and infrastructure. Furthermore, the most prevalent aspects of the PSS definitions by Annarelli et al. (2016) are customer needs, tangibility and intangibility, the systemic concept and networks and infrastructure. Therefore, once the customer needs are identified and the value proposition is formulated, the elements that mutually exclusively and collectively exhaustively describe the structure of a system that is PSS can be reduced to the most dominant definition, i.e., the seminal work of Mont (2004). In that definition, product, service, network and infrastructure, described by Pirola et al. (2020) "all" the PSS components, have to be intentionally designed to deliver value to the customer over its life cycle. However, PSS is more than just a collection of elements because

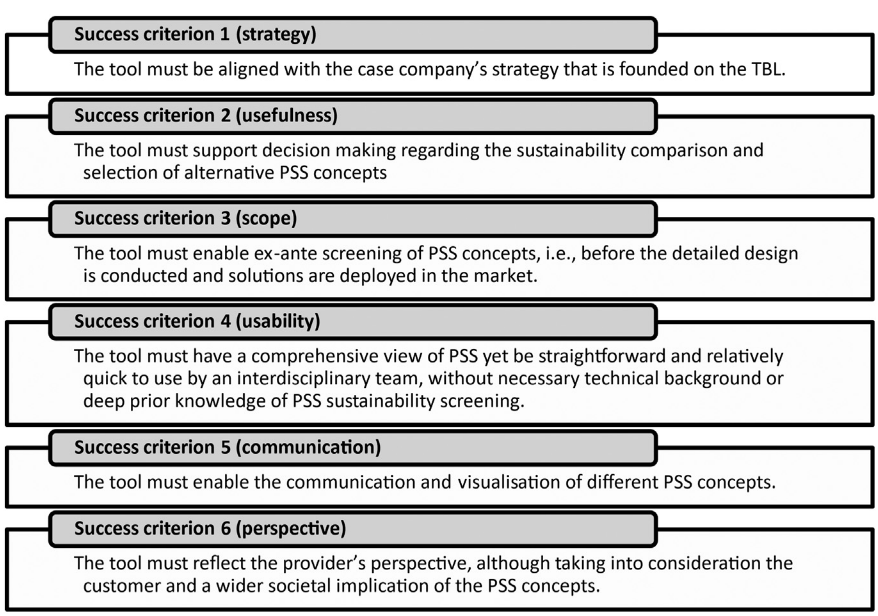


Fig. 3. Case company success criteria for the tool.

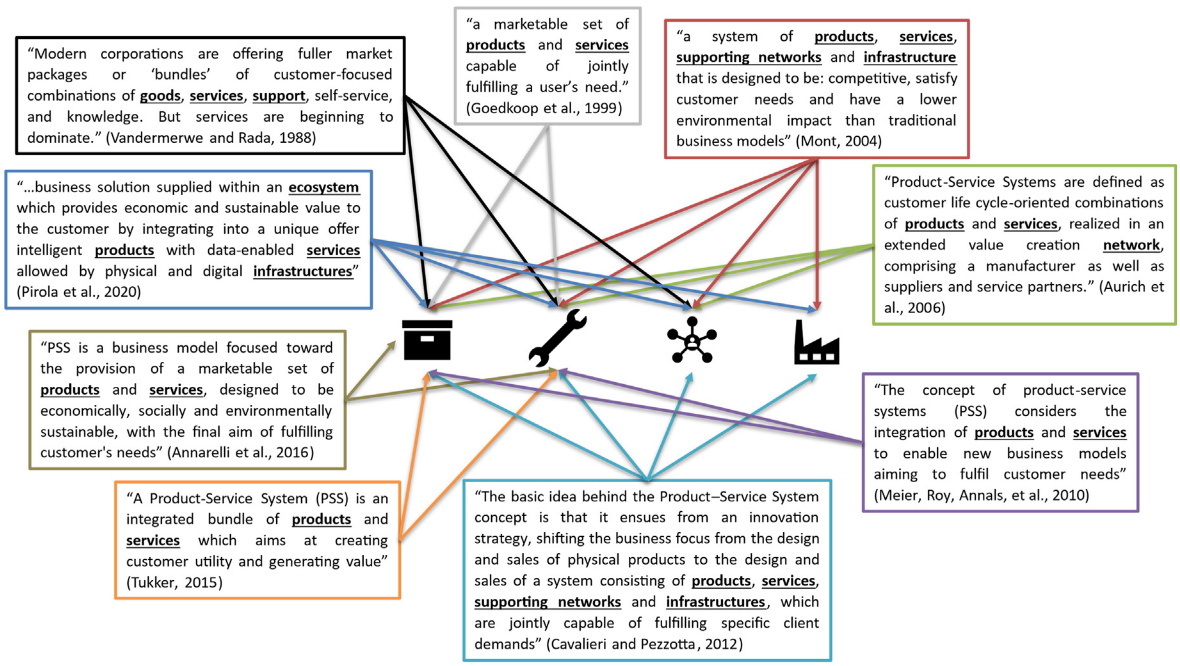


Fig. 4. An overview of proposed PSS definitions in the literature with highlighted PSS elements and depicted with pictograms (from left to right: product, service, network, and infrastructure).

the combination of elements should have a synergetic or super-additive effect (Kristensen and Remmen, 2019).

4.2.2.2. PSS sustainability. A common assumption in the PSS field is that sustainability would be achieved if the designers follow the design guidelines, however, real screening is lacking in the early design process (Doualle et al., 2020). PSS is neither inherently sustainable nor circular, and it has to be purposely designed (Pigosso and McAloone, 2015).

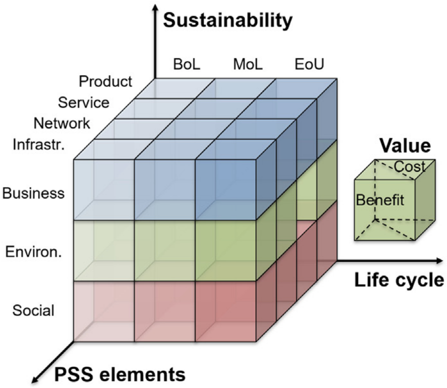
Although PSS has the potential to achieve a "triple-win" concerning the TBL of sustainability, there are very few attempts to assess PSS from the TBL perspective in literature (Chiu et al., 2018; Lee et al., 2012). Observed strictly from the manufacturing perspective, different PSS archetypes (i.e., product-oriented, use-oriented, and result-oriented) have different potentials for the reduction of environmental impact (Tukker, 2004), which has to be considered when selecting and designing concepts. Product-oriented PSS implies the sales of products with add-on services (e.g., consulting or maintenance. Unlike the product-oriented PSS, use- (e.g., renting, sharing and leasing) and result-oriented PSS (e.g., the focus is on the result without specifying the exact product) are distinguished through product ownership retention by the provider (Baines et al., 2007).

Sustainability is rarely treated as a primary root of value, it is rather seen as an add-on (Yang et al., 2017). Companies frequently comprehend sustainable value as the capacity to transform social and environmental value into business, but the social and environmental value should be seen not as enablers of economic value, but rather as standalone absolute values (Hart et al., 2003; Kristensen and Remmen, 2019). According to Bocken et al. (2015), a sustainable value proposition consists of the main dimensions: economic, social and environmental. Hart et al. (2003) define sustainable value as multidimensional "shareholder wealth that simultaneously drives us towards a more sustainable world".

A concept similar to sustainable value is the shared value (Porter et al., 2011) in which companies concurrently advance economic and social circumstances in the communities they operate. While (Baines et al. (2007) talk about the potential to decouple value creation from resource consumption through PSS, the concept of shared value (Porter et al., 2011) in which economic prosperity is coupled with social progressivity is often neglected in the PSS field (Merli et al., 2018). However, the significance of associating social issues (e.g., labour rights, social justice and communities) with sustainable PSS (e.g., social actors or stakeholder networks) is crucial to innovation and change (Chen, 2018). Both concepts share the same challenges, i.e., to decide which practices and actions to pursue and how to deliver the most value from the TBL perspective (Hart et al., 2003; Porter et al., 2011).

Table 1
Comments and the actions taken to address the feedback from step 1.4.

Feedback number and keywords	Action taken
1. Life cycle point of view	Adoption of the provider's life cycle perspective, as defined by Aurich et al. (2006), places most of the customer's activities in the provider's MoL, excluding the purchase (BoL) and prospective decommissioning (EoU).
2. Life cycle boundaries	PSS life cycle is adopted as the operating frame (Sundin, 2009), which is not necessarily tied to that of a product, nor is it in sync with that of a service (Wiesner et al., 2015). E.g., a machine manufacturer can agree with a customer to provide a use-oriented PSS (Tukker, 2004) for a period of time. Within that period the manufacturer might be forced to replace multiple products, to respect the availability-based agreement. Therefore, within the same PSS life cycle, products or services can have their respective life cycles (BoLs, MoLs and EoUs) within the MoL of the PSS life cycle, which can be upgraded or downgraded due to ever-changing customer requirements within the life cycle of a PSS.
3. Four dimensions	The implementation process was made more user-friendly by introducing an extra prior step (Sheet A, Fig. 7) which made it easier to use the tool by gradually building up all four dimensions through the implementation process.
4. TBL interpretation	A nested or interdependent TBL view (Isil and Hernke, 2017) is adopted to screen PSS concepts. The implementation process was made more iterative with questions referring to previous sustainability dimensions (previous layer of the BESST cube) after each layer is filled out.



Dimension	Definition
TBL sustainability	As defined by Elkington (1998)
Business (economic)	A condition in which economic capital is stable
Environmental	Maintenance and replenishment of natural capital
Social	Maintenance and replenishment of social capital
PSS elements	Main system elements (Mont, 2004)
Product	Products, technologies, nouns, the main tangible artefacts (things)
Service	Intangible artefacts, verbs (actions)
Network	Upstream and downstream actors in the value chain (people)
Infrastructure	Other products, systems, support technology (supporting things)
Life cycle	The progress of a PSS from its inception to disposal (Sundin, 2009)
Beginning-of-Life (BoL)	Includes design, procurement, production, assembly, distribution
Middle-of-Life (MoL)	Starts when the PSS is fully operational at the customer
End-of-Use (EoU)	Starts when the customer no longer needs the PSS
Value	Benefits versus sacrifices perceived (Toossi, 2011)
Benefit element	Drivers of positive impact to the TBL
Cost elements	Drivers of negative impact to the TBL

Fig. 5. The BESST cube for PSS concepts and the definitions of its dimensions.

4.2.2.3. PSS value. Over the years, the notion of value has become focal in the PSS field (Bertoni et al., 2017; Tran and Park, 2015). The value considerations are particularly important in the early stages of design, where value-driven design methodologies enable a more comprehensive awareness of the value of the total solution and help to avoid arriving at local optimum solutions (Bertoni et al., 2018).

As Chou et al. (2015) pointed out, to comprehensively assess the sustainable value of PSS, the connection between value and sustainability impact is a crucial factor to judge the sustainability performance of a PSS. Value should be used as a proxy for “PSS fitness” in the early-stage assessment, however, there is a lack of consensus on what aspects of value should be taken into account during the early-stage design assessment (Rondini et al., 2020).

A range of definitions of value exist, mainly based on the perceived benefits versus sacrifices (Toossi, 2011). Zeithaml's (1988) definition of value as the:” overall assessment of the utility of a product (or service) based on perception on what is received and what is given” remains the most prevalent definition. Value is a multidimensional concept that should not be reduced to only one form (monetary), or only one perspective (customer's), rather it should expand its focus beyond the limits of the company to include value for society and the environment (Kristensen and Remmen, 2019).

Many authors identify value in the same way as others define benefits, thus observing benefits and benefits missed (Yang et al., 2014), whereas according to the definition, value also consists of costs or sacrifices, therefore, value is created only when benefits surpass the costs (Figge and Hahn, 2004). This distinction is necessary also to avoid pursuing environmental or social benefits at any cost (Porter et al., 2011).

Tao and Yu (2017) suggest that the integration of sustainability in the life cycle systems shows promise for sustainable value creation. Value has a perplexed and ever-changing temporal perspective, thus it also has to be observed from a life cycle perspective. Xing et al. (2013) put value into the life cycle perspective of a PSS by defining it as life cycle performance over life cycle burden. Furthermore, when comparing value delivery involving products versus PSS, the window to deliver value in PSS is much larger for all the involved stakeholders, in all three dimensions of sustainability (Yang et al., 2014).

4.2.2.4. PSS life cycle. Life cycle thinking is a crucial concept for holistically developing sustainable PSS (Meier et al., 2010; Yang et al., 2014) and to guide decision-making for screening the PSS value over time (Xing et al., 2013). Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) are often used to calculate environmental impacts and economic costs of PSS (Lindahl et al., 2014), however, the focus on the whole life cycle in the early design process is missing in literature (Pezzotta et al., 2018), although being crucial for successful value delivery (Wuest and Wellsandt, 2016). As a part of the complete product life cycle, the prolongation of the life cycle of the offering in the market is one of the main benefits of this holistic view because it: (i) increases resource efficiency; (ii) introduces more customer touchpoints creating longer business relationships; and (iii) allows for data accrual that might stimulate innovation and provide know-how feedback (Meier et al., 2010).

The basic product life cycle framework is most often described from the cradle-to-grave perspective in three phases: Beginning-of-Life (BoL), Middle-of-Life (MoL) and End-of-Life (EoL) (Corti et al., 2016). BoL encompasses design, procurement, production, assembly, and distribution. MoL includes the use, maintenance, repair, after-sales services, and insurance. EoL comprises reverse logistics processes including collection, disassembly, remanufacture, recycling and disposal. However, some authors argue that a more detailed description might be necessary for PSS (Wuest and Wellsandt, 2016): the PSS life cycle is a combination of a product and a service life cycle management that have to be integrated and coordinated (Wiesner et al., 2015). The two life cycles are often not aligned nor established in a closed loop to feedback information between them and BoL, MoL, and EoL (Corti et al., 2016).

Table 2
Comments and the actions taken to address the feedback from Step 2.4.

Feedback no.	Action taken
5. Life cycle transition	The exact transition point between BoL, MoL and EoU is blurred in PSS literature (Wuest and Wellsandt, 2016). Part of the confusion stems from authors dealing with consumer vs. capital goods. The distribution phase of manufactured goods is often prone to different classifications into BoL and MoL. In the case of capital goods (e.g., industrial equipment) the distribution phase falls into the BoL of a PSS, as such goods generate most of their value in use (Toossi, 2011) or through utilization, rather than ownership. Consumer goods discussions often place the distribution phase in the MoL of a PSS. For clarity in the tool implementation, the transition points between the three main phases are clearly defined in Fig. 5.
6. Repetitive	The implementation process is repetitive, but only for the first concept that is being screened. Once the next concept is screened, most of the cost and benefit drivers might remain unchanged in many alternative concepts. When put into the context of the PSS development duration, which may last for years in the case company's industry, the time required to fill out the BESST cube is relatively short.
7. Definitions	All the dimensions are clearly defined and presented in Fig. 5 which was then made available to the participants in the next AR cycle.
8. Prompts	The recommended implementation process steps were detailed and streamlined to include questions and prompts for easier workshop facilitation, as presented in Fig. 7.

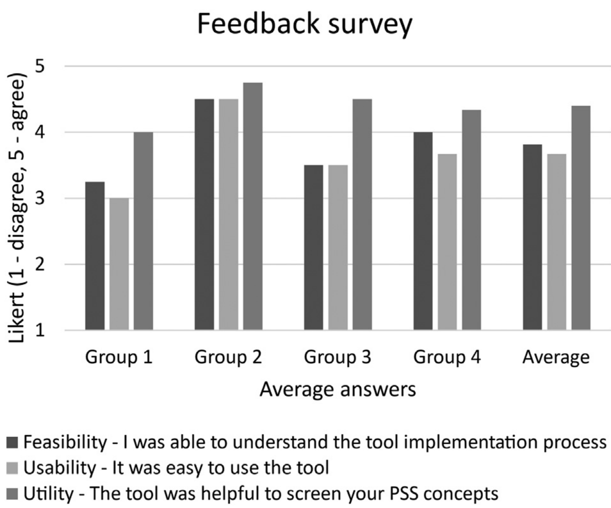


Fig. 6. Results of the student survey after the workshop.

Aurich et al. (2006) distinguish between the provider and customer life cycle perspectives, as they start at different points in time, which are the design for the manufacturer and the purchase for the customer. The customer is mostly focused on the usage phase, therefore, the provider should emphasize the same phase (Wuest and Wellsandt, 2016).

In summary, the key findings of the literature review carried out in this step are: (i) limited consensus on how to describe the main elements of PSS: product, service, network and infrastructure are selected as the main building blocks of a PSS concept, (ii) need to screen PSS concepts in the early design stages according to the TBL perspective, (iii) a value perspective is considered crucial when screening PSS concepts, and (iv) need to support the design and evaluation of PSS concepts from a life cycle perspective, with the beginning, middle and end of life stages.

4.2.3. Step 1.3. Development of the first version of the tool

The first version of the tool consisted of the four main dimensions: PSS elements, the TBL, value and the life cycle that had to satisfy the six elicited success criteria from the case company related to strategy, usefulness, scope, usability, communication, and perspective.

In this research, the TBL sustainable value of a PSS concept is defined as a function of cost and benefit in the three dimensions of sustainability (i.e., social, economic and environmental) over time, for each of the four PSS elements (i.e., product, service, infrastructure and ecosystem). The provider's perspective on the life cycle is adopted to screen PSS concepts, and it is split into BoL, MoL, and EoL. However, a more accurate term for replacing EoL would be the End-of-Use (EoU), which refers to instances in which the user can return a product at a point in the life cycle before its usefulness has perished (Östlin et al., 2009).

4.2.4. Step 1.4. Evaluation of the first version of the tool

The principal feedback and improvement opportunities identified related to (1) (as shown in Table 1) the lack of clarity on the life cycle point of view, (2) the indistinguishability between the product, service and PSS life cycle, (3) the ungraspability of the four dimensions at once and (4) the indistinct interpretation of the TBL.

4.3. Cycle 2: practical development

The second and the third AR cycles in the following sections include the descriptions of the development and evaluation steps (steps 2.3., 2.4., 3.3. and 3.4. explained in the Methodology).

4.3.1. Step 2.3. Development of the second version of the tool

The Business, Environmental and Social Screening Tool (BESST) for PSS concepts was proposed as a three-dimensional visual representation combined with the fourth value dimension (Fig. 5). The examination of

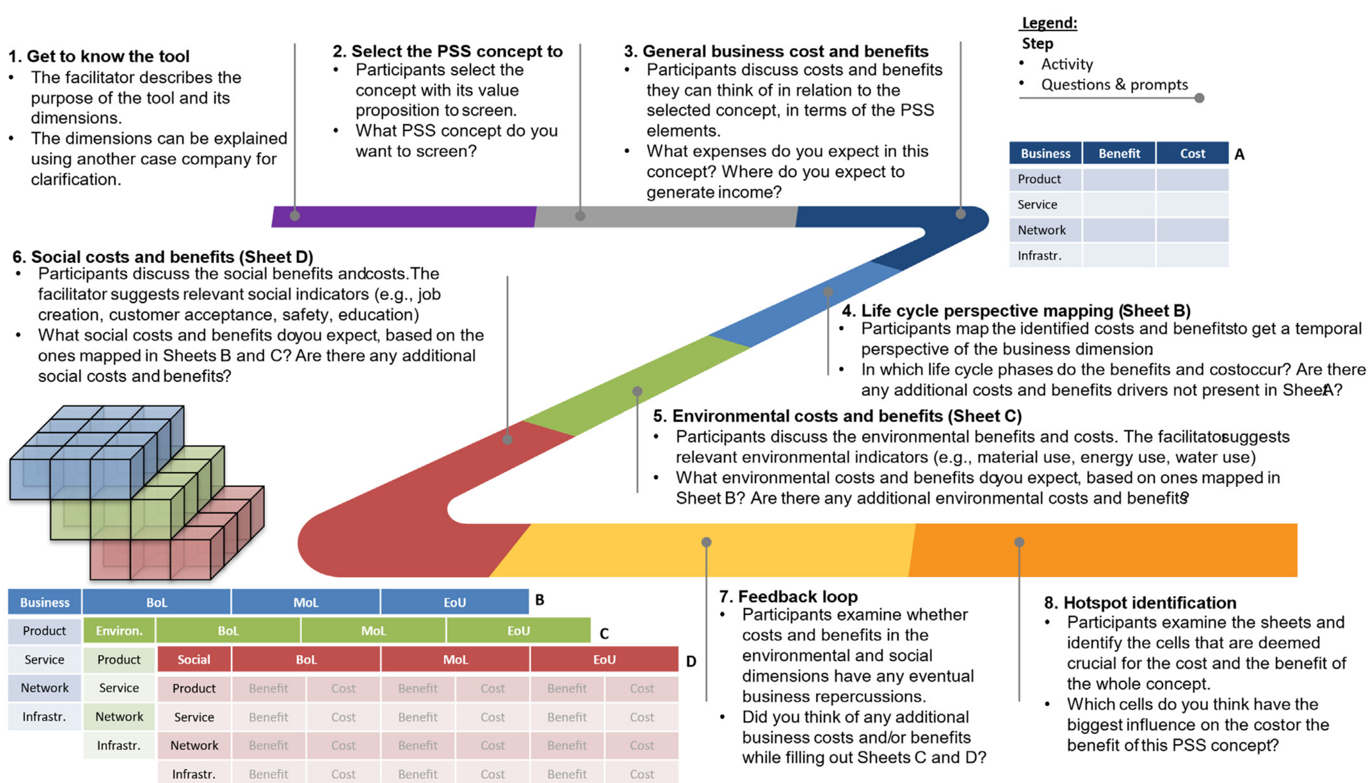


Fig. 7. Recommended implementation process. The BESST cube layers are sliced into three sheets (B, C and D) with a pre-step (Sheet A) to support the process.

Table 3
Actions taken to capture the improvement opportunities from step 3.4.

Feedback no.	Action taken
9. Examples	This feedback is incorporated in the first step of the recommended implementation process in Fig. 7.
10. Risks	It is recommended to map risks in the cost category with special markings.
11. Duality	It is recommended to map such costs and benefits in all the cells where they apply to have a complete overview.

the PSS elements over its life cycle in the three sustainability dimensions provides a comprehensive picture of the benefits and costs of a given concept from the provider's perspective, supporting decision-making.

In this baseline, a PSS concept can be represented by 36 dice forming the cube, where each dice holds information about its value, i.e., benefit and cost, totalling 72 data points to screen a PSS concept. The division of a life cycle into cost elements was proposed by Schuh et al. (2009), who argued that a cost element determines costs incurred by resource consumption in a specific life cycle stage. This work expands the existing cost elements to cover all three pillars of sustainability as well as introducing benefit elements. Therefore, cost and benefit elements determine the economic, environmental and social cost and benefit incurred at each of the three stages of the life cycle for all four PSS elements.

The tool also utilizes the concept of vertical coherence (Joyce and Paquin, 2016) introduced in the triple-layered business model canvas, which supports the alignment of cost and benefits across the three sustainability layers of the BESST cube.

Table 1 describes the implementation of the improvement opportunities identified in step 1.4.

4.3.2. Step 2.4. Evaluation of the second version of the tool

Several improvement opportunities emerged from the workshops in the tool evaluation, where four different implementation processes were tested. The main improvement opportunities concerned (5) (as shown in Table 2) the transition point between the three PSS life cycle phases, (6) the implementation process repetitiveness, (7) the exact definitions of each dimension and (8) the lack of prompts to facilitate the implementation process.

The implementation processes in the workshop with students differed in terms of the starting points (i.e., the four dimensions of the BESST cube) and the sequence of the subsequent steps.

By analysing the data gathered through participant observation and the survey, the dominant implementation process was selected as the one used by Group 2, depicted in Fig. 6, which rated the feasibility and usability of their implementation process noticeably higher than the other groups. That implementation process is presented in Fig. 7, and its main difference from the other implementation processes is the introduction of the pre-step (Sheet A).

4.4. Cycle 3: industrial development

4.4.1. Step 3.3. Development of the third version of the tool

Table 2 describes the actions taken to implement the improvement opportunities from step 2.4.

4.4.2. Step 3.4. Evaluation of the third version of the tool

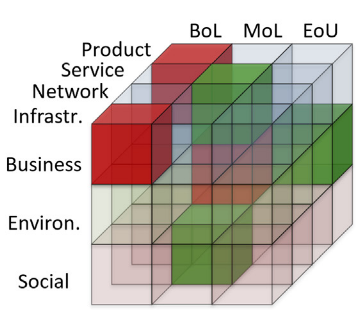
Improvement opportunities identified in the evaluation with the case company included the need for (9) more examples of what the dimensions refer to in other companies, (10) a definition of the role of risks (potential costs) in the tool and (11) clarification of the duality of costs and benefits, as some of the spread across different dimensions with different impacts (e.g. monetary cost of training of technicians in the BoL brings social benefits in MoL).” Table 3 summarises the actions taken to address the improvement opportunities.

4.5. Case application

The BESST was used to screen a PSS concept brought forward by the case company. The screened concept was a use-oriented PSS where a food-processing machine is leased for a set period with a promised performance, but the customer is responsible for the function fulfilment.

Fig. 8 depicts the stage in the BESST implementation process where the hotspots have been identified for the given PSS concept in terms of benefit and cost drivers that most significantly influence this particular concept. The hotspots can be defined as concerns of significant impact potential (Bertoni, 2019). The crucial identified hotspots are depicted in Fig. 8 with two colours, green for the positive hotspots, and red for the negative hotspots, which are coloured in various dice of the BESST cube.

Arguably the most concerning negative hotspot for the case company is the monetary cost and related risks of the infrastructure in the BoL of PSS, for two reasons. First, due to the lack of capabilities to develop and integrate such infrastructure involving many different elements internally such as all the monitoring equipment, software to support automatic periodical billing, software to track and manage the service agreements over time, but also the more material-intensive infrastructure in terms of establishment of additional repair facilities and tools, as well as the expansion of the logistics infrastructure to cover the increased need for service. Second, due to the uncertainty concerning the scale of the future PSS market, i.e., the number of customers that the infrastructure must be able to support in the long run. Both challenges could be ameliorated by entering partnerships and sharing the responsibilities within the actor-network. Furthermore, the first challenge could be addressed either by internal capabilities development or the acquisition of external capabilities, while the latter



Data point coordinates in the cube	Benefit / cost drivers
Business – BoL – Product – Cost	E.g., cost of retaining the ownership, financing costs, insurance, taxes, reduced initial cashflow
Business – BoL – Infrastr. – Cost	E.g., cost of support artefacts (IoT and monitoring equipment, recurring payment and CRM software, process and instrumentation equipment)
Business – MoL – Service – Benefit	E.g. recurring and more stable revenue stream, customer lock-in, more customer touchpoints, more feedback on machine operation
Environ. – MoL – Service – Cost	E.g. more emissions due to travel, materials, energy, chemicals and water used in service operations
Environ. – EoU – Product – Benefit	E.g. reduced material use by enabling take-back, refurbish, resell, reuse, recycle, or responsible disposal
Social – MoL – Network – Benefit	E.g. better training for technicians, less injuries, more service jobs, ease of use, customer retention

Fig. 8. Examples of hotspot benefit and cost drivers identified through PSS concept screening in the case company.

Author(s)	Value (benefit-cost)	PSS elements	Life cycle perspective	SC 1 (TBL strategy)	SC 2 (usefulness)	SC 3 (scope)	SC 4 (usability)	SC 5 (communication)	SC 6 (perspective)
(Lee et al., 2012)	✗	✓	✗	✓	✓	✓	✗	✓	✗
(Kim et al., 2013)	✓	✓	✓	✓	✓	✗	✓	✓	✓
(Xing et al., 2013)	✓	✗	✓	✗	✓	✗	✗	✗	✓
(Abramovici et al., 2014)	✗	✗	✓	✓	✓	✗	✗	✓	✓
(Yang et al., 2017)	✓	✗	✓	✓	✓	✗	✓	✓	✓
(Chiu et al., 2018)	✓	✓	✓	✓	✓	✓	✗	✓	✓
(Bertoni, 2019)	✓	✗	✗	✓	✓	✓	✓	✓	✓
(Rondini et al., 2020)	✓	✓	✗	✗	✓	✓	✗	✓	✓
(Doualle et al., 2020)	✓	✗	✗	✓	✓	✓	✗	✗	✓
BESST PSS	✓	✓	✓	✓	✓	✓	✓	✓	✓

Fig. 9. Comparison of the BESST with other existing tools for PSS sustainability screening with respect to the elicited success criteria (SC).

challenge could be addressed by thorough market analysis and customer interviews to estimate the size of the addressable market and attempt to project it in the future.

The positive hotspots are many in all three dimensions of sustainability and they add up to a potentially very beneficial business model for the case company. Most of the benefits manifest in the MoL of PSS which ought to become a prolonged period of product useful life and revenue stability from locked-in customers relieved from many of the service responsibilities and difficulties that were present in the pure product sale.

5. Discussion

The academic contribution of the novel tool manifests in eliciting and connecting the four crucial dimensions identified both from literature and empirically for sustainability screening of PSS concepts in the early stages of PSS design. This research contributes to a deeper understanding of sustainable value considerations in PSS design, and it enables industrial decision-makers to align the new business development to the company's strategy, which is based on the TBL.

The comparison of the BESST with the existing tools (presented in Section 4.1) with respect to the elicited success criteria (presented in Section 4.2) can be seen in Fig. 9. The comparison connects previously analysed existing tools in collaboration with the company representatives, the success criteria formed based on the analysis and the newly developed BESST which satisfied all the success criteria as judged by the company representatives and the authors. This comparison also serves as initial verification of the newly developed tool.

Elements of every tool examined were deemed useful for the application, however, most of the existing tools were considered too time- and resource-consuming to be applied in the case company by the authors and the company representatives. This is due to either lack of capabilities or lack of information in the company required to utilise the existing tools. Moreover, many of the tools lack the life cycle perspective, detailing to the level of the PSS architecture or a reflective screening perspective.

Numerous strengths of the BESST tool were discussed with the company representatives during its application. The tool was judged distinctly helpful to visualising and communicating the otherwise abstract phenomenon of PSS holistically, spurring many relevant discussions, especially about the eventual rebound effects, further refinement of the particular areas (dice in the BESST cube) of the PSS concept and even emergence of new concept ideas.

The applicability of the tool is judged to be plausible, even outside of the scope of its pre-determined success criteria, namely for ex-post screening and screening of wider business development initiatives, rather than PSS alone. Although the granularity level of the concept screening tool suffices the case company success criteria, the BESST tool's modular structure affords possible adjustments to accommodate for a more detailed screening, should the need arise (Fig. 10).

The four sheets utilised in the implementation process (Fig. 7) have been recognized as a helpful step to define the total cost and benefit of ownership (TCO and TBO) for any given concept, not only business-related but in all three dimensions of sustainability.

Practitioners with different backgrounds, knowledge and roles in the companies might have different perceptions of value, especially since strict indicators were not defined in each of the cells. A common example when using the tool is that people with commercial backgrounds overly focus on the business layer of the cube. Another common pattern is that the righter (towards the EoU layer) and lower dice (towards the social layer) are positioned in the BESST cube, the more obvious is the lack of competencies to identify and ameliorate the cost or capitalise on the benefit of the hotspot. A similar pattern can be observed with the infrastructure layer, which is more intuitive to identify the benefits and costs but lacks the methods to address the challenges arising in it. A possible reason for that observation is that the existing tools and practices do not focus as much on the PSS infrastructure, social and EoU aspects. The indicators were not defined to avoid constraining the thinking about the hotspots and allow for free ideation. To bridge this difference in perceptions, the recommendation is to include people with different backgrounds in the workshops while conducting the implementation process to ensure that the screening is considered from multiple angles.

Another important learning from the application of the final version is the importance of a completely clear definition of PSS concept alternatives before the concept screening with BESST. This is due to the possibility of the emergence of new sub-concept ideas during the screening process. This can result in an even better final concept but can also cause a new iteration of the initial concept development and prolong the whole process of PSS design.

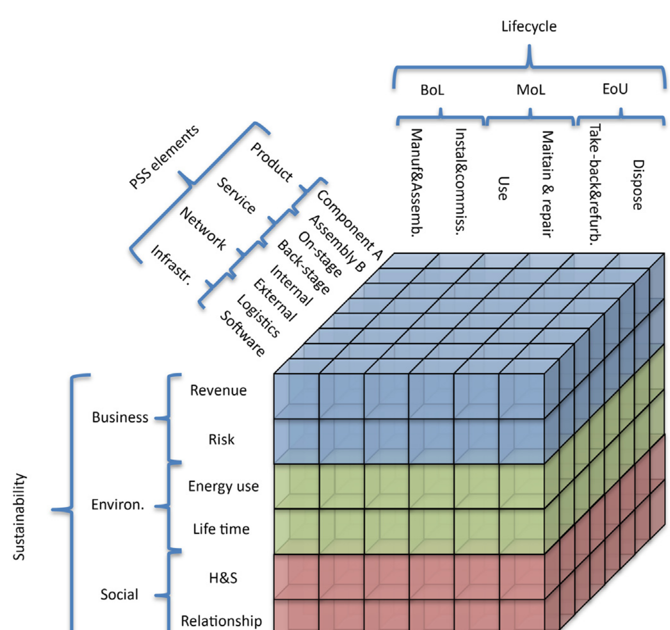


Fig. 10. The BESST expanded for more granularity with exemplified sub-dimensions.

The limitations of the BESST tool are related to the static and fragmentary qualitative assessment of multidimensional PSS concepts. Thus, the concept screening as defined here is an aggregation of unconnected pieces that build up the whole PSS concept (Lee et al., 2012). Further limitations relate to the nature of AR which is conducted in a single case company. To ensure that the tool matures to general applicability across the capital goods manufacturing industry, the authors propose multiple case studies with a recommendation to conduct them both in smaller and larger companies than the one described here, and with different PSS archetypes (product- and result-oriented).

6. Conclusion

This paper introduced a decision-making tool for the ex-ante qualitative screening of PSS concepts with respect to TBL sustainable value along their life cycle. The BESST tool was built based on the literature and empirical findings through three AR cycles. The tool connects four dimensions identified in the literature as crucial for the sustainability screening of PSS concepts: PSS elements, PSS life cycle, PSS sustainability and PSS value and satisfies the case company success criteria elicited through the interviews. The industry practitioners involved in the study perceived the tool and the associated implementation process as an effective and efficient approach to screen the sustainability of PSS concepts. To address the tool's limitations, further work could focus on studying the connections and trade-offs between individual elements (dice) in the BESST cube. Other directions could tackle the tool's upgrade to contribute to the Circular Economy by focusing on R-strategies, as PSS is seen as a possible key means to circularity. The BESST is to be further evaluated in other manufacturing companies, to ensure generalisability.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Impacts, synergies, and rebound effects arising in combinations of Product-Service Systems (PSS) and circularity strategies

David Sarancic[a,*], Julija Metic[a], Daniela C. A. Pigosso[a], Tim C. McAloone[a]

[a]*Technical University of Denmark (DTU), Department of Civil and Mechanical Engineering, Nils Kopples Allé 404, 2800 Kgs. Lyngby, Denmark*
* Corresponding author. Tel. +4545254153. *E-mail address:* dasar@dtu.dk

Abstract

Product-Service Systems (PSS) are potentially the pivotal enablers of the Circular Economy (CE), a promising approach towards sustainable development. Yet, in practice, and when not designed mindfully, the development of PSS can result in limited benefits to the triple-bottom-line of sustainability for a manufacturing company, not least due to the sub-par return on investment or socio-environmental rebound effects (RE) caused by negligent product use or lower customer acceptance. Approaching sustainability through CE requires systemic and concurrent consideration of multiple circularity strategies during PSS design. However, existing research predominantly focuses on isolated circularity strategies rather than bundling them together to achieve super-additive effects. This article explores the impacts, synergies, and RE arising in different combinations of PSS types and circularity strategies in the early design stages. The findings stem from the state-of-the-art literature review, followed by a three-step analysis that utilises the Business, Environmental, and Social Screening Tool (BESST) for PSS and the Rebound Effect Framework (REF) to discern seven identified configurations of PSS and circularity strategies in a capital good manufacturing company.

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Keywords: circular economy; circularity strategy; product-service system; business model; rebound effects

1. Introduction

Circular Economy (CE), as opposed to the current linear ('take-make-use-dispose') economic system, is considered one of the crucial approaches to contribute to sustainable development [1,2] The transition to CE in which economic growth is decoupled from virgin resource consumption has become one of the principal initiatives for reaching the 2030 sustainability targets in Europe [3]. This decoupling can be achieved with the application of CE strategies [2]. Several CE strategies can be used individually or in combination with each other to reduce the consumption of natural resources and contribute to circularity, such as refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover [4,5]. However, environmental burdens are not automatically achieved by the utilisation of CE strategies, as discussed in the existing literature [6,7].

Out of the listed strategies, product-service systems (PSS) which fall under the 'rethink' CE strategy are considered a primary means of changing the current economic system [8]. PSS are life cycle-oriented and marketable combinations of products and services supported by the infrastructure and the network of actors, designed to deliver more value than traditional product sales [9] PSS show great potential to positively impact the triple-bottom-line (TBL) of sustainability [9,10] but are not by default more sustainable than the sole product [11]. Therefore, their impacts must be considered from a systemic perspective already in the early design stages [10].

In literature, the CE strategies (including PSS) and their impacts are often considered individually, and their combinations remain unexplored [12], even though there is evidence that the combinations of CE strategies can help companies achieve higher levels of circularity and resilience during crises [13].

Despite several contributions aiming to support the creation of CE business models (see e.g., [14,15]), there are only initial attempts in the literature to explore CE strategy combinations and their impacts. Multiple retrospective case studies with nine existing companies have been conducted to map how different types of PSS relate to different circular strategies [16]. Another

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case study has been conducted to identify and analyse CE strategy combinations and the role of PSS in the case of Riversimple, a mobility-as-a-company, using the Circularity Compass [17]. Both articles provided invaluable insight into different combinations but with hindsight, in an ex-post analysis of existing solutions. However, scarce attention in the literature has been given to the consideration of the TBL impact of different combinations of CE strategies and PSS in the early design stages of circular PSS offerings [18].

Furthermore, there is a gap in the literature to observe what are the synergies and antagonisms that stem from different CE strategy combinations, i.e., how the concurrent utilisation of two or more strategies can yield super-additive effects and what rebound effects (RE) can they possibly induce together. RE happen due to behavioural or a systemic response in which the actual impact savings of an intended initiative are smaller than anticipated [19]. RE manifest in many shapes and forms, moreover, they can be initiated by various actors, across many levels and types - which makes them hard to identify and measure [20]. There is a limited understanding of the occurrence of RE in the context of CE and PSS in the literature [20], and options to mitigate their impact without various CE strategies are underexplored [21].

This research sets out to explore how to support manufacturing companies in the consideration of different combinations of CE strategies and PSS types in the early stages of design, a priori to the deployment of the offering in the market. The ex-ante consideration is deemed important as research shows that a company's environmental awareness has a pivotal role in the contribution of PSS to circularity [22]. Therefore, the primary focus of this research is the identification of combinations' impact, synergies, and potential RE through the analysis with the existing tools.

2. Methodology

This research is exploratory and has been conducted in collaboration with a single-case capital goods manufacturer in the food processing industry. This case company has been selected because: (i) it is considered typical of many other equipment manufacturers, (ii) of the availability of decision makers to provide input, (iii) it is at an early stage of PSS design, and (iv) of authors' connections through previous action research [23,24]. The selected company hopes that PSS would positively contribute to their TBL strategy, and therefore, they articulated the need to systematically assess impact, synergies, and possible RE in different combinations of CE strategies and PSS.

The actions in this research have been structured in four main steps: (1) preliminary literature review, (2) selection of configurations of PSS and CE strategies deemed feasible for further analysis in collaboration with the case company, (3) the expert analysis of TBL impact (positive and negative) of the selected seven configurations, and (4) the expert analysis of the synergies and possible RE for the selected configurations.

Step 1. Building on the previous systematic literature review conducted by the authors [20] a further review was executed using the Scopus database which targeted the following keywords and their synonyms: product-service system, circularity strategy, and RE. The literature review aimed to study the state-of-the-art literature on combinations of different CE strategies with PSS and potential RE. The most relevant articles were selected due to their comprehensiveness and sharp focus on the combinations of CE strategies and were summarised in the Introduction.

Step 2. The selection of configurations, i.e., the combinations of different CE strategies that might go well together was conducted by using an adapted version of the Framework for analysing the relationship between CE strategies (listed in the Introduction) and PSS types [16], where the eight PSS types are defined based on Tukker [25]. This framework was used to select seven configurations of CE strategies for further analysis.

Step 3. Upon the selection, seven configurations were designed and screened to find the drivers of positive and negative impact on the TBL. The screening was done employing the Business, Environmental, and Social Screening Tool (BESST) [23]. BESST is a comprehensive screening tool constructed to address the relevant aspects that were missing in the existing tools beforehand, such as the complete view of the TBL, PSS elements, life cycle stages and value (Fig. 1.). The tool enables practitioners to anatomise the configuration into 36 data points (smaller dice) to get a clear picture of where the most significant positive and negative impacts (hotspots) occur.

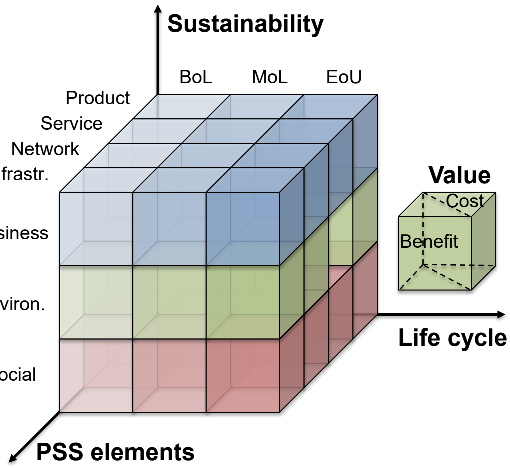

Fig. 1. BESST [23].

Step 4. The configurations were further analysed to map out synergies and RE between different combinations of CE strategies. This analysis builds on the previous two steps and uses the Rebound Effect Framework (REF) [20] to identify triggers, drivers, and mechanisms (Fig. 2). This framework was chosen due to its strong theoretical background and holistic focus on RE stemming from a systematic literature review.

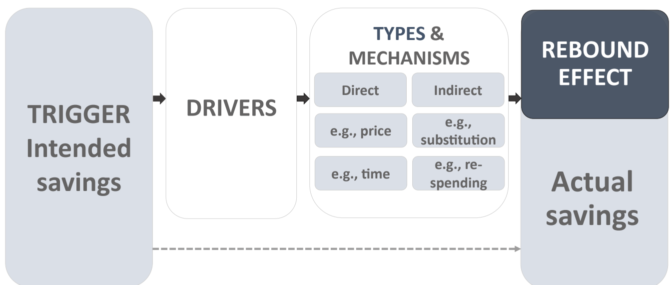

Fig. 2. REF [20].

3. Configurations selection

The selected configurations of PSS types and CE strategies can be seen in Fig. 3. Each of the seven configurations is showcased with a distinct hatching pattern and colour. There are many possible combinations of CE strategies and PSS types, and they might overlap. In practice, a company would often simultaneously run several configurations to satisfy the needs of different customer segments [16].
The case company prefers to use two of the CE strategies in several configurations, namely 'reduce' and 'repair & maintain', while almost all the PSS types apart from product pooling appear to be feasible. Pooling is not considered feasible in the industry where the case company operates (food processing) because of the hygienic and trade secret restrictions that would be violated if the product is used simultaneously by several users.
The CE strategies 'refuse', 'recycle', and 'recover' have been left out of the analysis because they were deemed unfeasible from the case company's perspective. The 'refuse' strategy in which the function should be delivered by a radically different product or technology (e.g., replacing DVDs with streaming services) was not deemed realistic at this point and in the context of the case company. Finally, the 'recycle' and 'recover' strategies were considered beyond the scope of the foreseeable future initiatives.
The 'upgrade' strategy[16]was considered particularly promising in this case due to its potential to have a significant impact on the TBL of the large installed base of products.

4. Configurations analysis with the BESST

The seven identified configurations have been analysed using the BESST (shown in Fig. 4 together with descriptions of configurations). For each of the configurations, positive and negative hotspots have been identified and coded according to the dice where they occur (e.g., Business-MoL-Service, where MoL stands for 'Middle-of-Life') in the BESST to get a clearer picture of the benefits and criticalities that accompany each configuration. For example, in the first configuration (blue hatching), 'product related service' is combined with 'reduce' and 'repair & maintain'. In practice, the product is sold to a customer together with a time-limited maintenance contract that can include periodical inspections of wearable and consumable parts by the providers, recommendations and sales of spare parts and the actual repair should the product break. These preventive actions help ensure greater product availability due to timely maintenance and smoother (e.g., properly lubricated) operation that consumes less energy and produces less scrap and excess heat. The benefits (positive hotspots) and costs (negative hotspots) of such a configuration mostly manifest in the MoL of the offering. The benefits materialise through an additional revenue stream from the provider (business), less energy use and longer life (environment), and more customer touchpoints (social) because of more frequent interaction about maintenance and spare parts which creates a stronger relationship. While the costs manifest through risks taken over by the provider, where the price and the timing of a possible repair intervention at customers' sites are difficult to predict (business). More travel is required due to the inspection visits which can have a significant environmental impact (environment). There is also a possibility of a loss of technician jobs at the customer, as the provider takes over maintenance and repair activities (social).

		Circular strategies							
		Smarter product use and manufacture		Extend lifespan of a product and its parts					
		Rethink	Reduce	Upgrade	Reuse	Repair & maintain	Refurbish	Re-manufact.	Repurpose
		Use multi-functional products, more intense use of product's capacity	Increase efficiency by using fewer resources & energy in manuf. and use	Improving product function with respect to previous one	Product in good function, use in original function by new user	Correct defective part to return it to its original function	Return worn part or product to satisfactory working condition	Return worn part or product to original specification	Use a part of product in a new product with different function
PSS types: Product-oriented	Product related service (e.g., inspection contract)								
	Product related advice (e.g., monitor. & training)								
PSS types: Use-oriented	Product lease								
	Product sharing/renting								
	Product pooling								
PSS types: Result-oriented	Pay per service unit (e.g., €/h or €/kg)								
	Outsourcing/activity management								
	Functional result (e.g., X€/job)								

Fig. 3. Configuration based on PSS types, accompanied by a combination of different CE strategies. Seven configurations are represented with a distinct hatching pattern and colour. Framework adapted from [16].

Config.	Configuration description	Positive hotspots (benefits)		Negative hotspots (costs)	
		Coord. (BESST)	Description of main benefits	Coord. (BESST)	Description of main costs
1.	Sell products and time-limited contracts incl. repair, maintenance, and spare parts to ensure greater product availability, and optimal operation and energy use. Benefits and costs both manifest mainly in MoL due to increased service activities.	Business-MoL-Service	Additional revenue stream	Business-MoL-Service	Risk of variable costs
		Environ.-MoL-Service	Less energy use, prolonged life	Environ.- MoL-Service	More travel, i.e. pollution
		Social-MoL-Service	More customer touchpoints	Social-MoL-Network	Loss of internal service jobs at the customer
2.	Sell products and monitoring equipment to get data about product use. Provide advice, training, updates, and upgrades based on data. Benefits manifest through increased knowledge sharing and data-based actions. Cost incur in mainly in BoL to establish the monitoring infrastructure and acquire data analytics capabilities.	Business-MoL-Infrastr.	Getting use insights for future development	Business-BoL-Infrastr.	Cost of monitoring equipment
		Environ.-MoL-Product	Enable optimised use due to monitoring	Environ.-MoL-Infrastr	More energy spent on monitoring
		Social-MoL-Network	Trained personel at customers	Social-MoL-Network	Customers afraid to share data
3.	Lease product and take responsibility for monitoring, preventive maintenance and repair. Benefits similar to the above configurations, but also evident through stable subscription revenue over time. However, costs and risks are introduced with additional responsibility as well as investment into product ownership retention.	Business-MoL-Service	Predictable, recurring revenue	Business-BoL-Product	Cost of ownership retention
		Environ.-BoL-Product	More intensive use by the customer to make the most of the lease	Environ.-BoL-Product	Building more material intensive (robust) product
		Social-MoL-Service	Less injuries because professionals do the service	Social-MoL-Network	Intensity of work increases for service employees
4.	Repeatedly rent several products. Restore the products and their parts between the rents. Benefits manifest through the flexibility of offering in terms of scalable capacities when needed, new markets, and lower access bar. Costs incurred due to increased logistics and initial infrastructure investments to handle the more frequent turnover of products.	Business-BoL-Network	New markets open for smaller customers or seasonal production	Business-BoL-Infrastr.	Build additional storage, workshops and tools
		Environ.-MoL-Infrastr.	Infrastructure can be shared for many products.	Environ.-EoL-Service	Increased logistics operations
		Social-BoL-Network	Lowering access bar for customers	Social-EoL-Network	Hygienic challenges when changing users
5.	Instal products at a customer and charge according to the use level. Take responsibility for monitoring and preventive maintenance and repair. Many shared benefits with config 3. Moreover, benefits through the ability to streamline product operation according to customer needs and ensure customer lock-in. Costs due to the complexity of monitoring and pricing schemes, and difficult to predict earnings.	Business-MoL-Service	Recurring revenue	Business-MoL-Service	Difficult to predict revenue
		Environ.-MoL-Service	Streamlined product operation	Environ.-MoL-Service	More service operations to keep the product running optimally
		Social-MoL-Network	Longer lasting relationships	Social-MoL-Network	Possible lack of trust from customers due to feeling of being surveilled
6.	Find third-party service providers to cover upgrades, repair, refurbishment, and remanufacturing. Benefits due to rapid increase in market share coverage through partnership and opportunities to gain insights into more customer operations. Costs due to increased relationship management and possible distancing from customers because of the third party in between.	Business-BoL-Network	Secure more projects because of expanded capabilities	Business-MoL-Service	Losing a part of the service business
		Environ.-EoL-Product	Use products and parts that would otherwise go to waste	Environ.-MoL-Network	More pollution due to inefficiency in ecosystem coordination
		Social-BoL-Network	Form external partnerships and get knowledge from them	Social-MoL-Network	Burden of partnership coordination
7.	Agreement to deliver a result to the customer, regardless of the product used. Benefits stem from a high level of offering customisation which enables higher margins. Costs can incur due to unforeseen overheads, risks and and increase in responsibilities to deliver the total solution on time.	Business-MoL-Service	The highest profit margins	Business-BoL-Infrastr.	Large initial investment to ensure product performance
		Environ.-MoL-Product	Flexibility to combine less impactful modes to get results	Environ.-BoL-Infrastr.	All the infrastructure to support (many) offerings has to be built
		Social-BoL-Network	Eliminated unnecessary communication with customers	Social-MoL-Network	Stressful for employees due to expected performance

Fig. 4. Analysis summary of the seven configurations using the BESST. BoL stands for the 'Beginning-of-Life' and EoU stands for 'End-of-Use'.

5. Synergies and RE in different configurations

The seven configurations were further analysed using REF to map synergies and RE of PSS types and CE strategies (Fig. 5).

Config.	Synergies	Rebound effects – Triggers	Rebound effects – Drivers	Rebound effects – Mechanisms
1.	Timely maintenance and repair can increase product availability and less energy when worn parts are quickly replaced.	- Increase in resource efficiency - Decrease in energy use	- Increase in profits - Increase in interaction with customers - Easier access to spare parts	- Output - selling more spare parts, even when not needed, because of more frequent interaction with customers
2.	Leveraging technologies (IoT) to be closer to customers and empower them through training	- Increase in resource efficiency - Innovation and Investment - Data based improvement	- Increase in profits - Information accessibility - Time savings	- Re-investing into data collection, advice and training – possible data breaches disturbing the competitive advantage
3.	Incentive to design sturdier machines because the ownership is retained and salvage value should be as high as possible.	- Increase in resource conservation - Increase in resource and product utilization	- Convenience - Easier access to repair and maintenance - Time savings - No obligation of ownership	- Motivational - careless use because the machine is not owned by the customer
4.	Bigger machine changeover can enable builing a stock and processes for refurbish, remanufacture and repurpose	- Increase in product and resource utilization - Increase in resource efficiency	- Convenience - Time savings - More often access to machines	- Substitution to more transportation, as well as installation and comissioning operations overpowerring the benefits achieved with renting
5.	Incentive to design easy-to-use and easy-to-service products to save time and money on service visits.	- Increase in efficiency - Increase in product and resource utilization	- Time saving - Convenience - Cost savings	- Substitution to having an underustilised machine that is rarely turned on by the customer
6.	Possibe to offer a wider portfolio of services in collaboration with external partners.	- Increase in resource efficiency - Increase in product and resource utilization	- Time savings - Convenience - Cost savings - More often access to machines	- Substitution - thrid party providers can cannibalise on own business
7.	A possibility to truly decouple value creation from resource consumption, especially when providing the offering to many customers and suporting it with the same network and infrastructure.	- Increase in resource efficiency - Increase in resource conservation - Increase in resource and product utilization	- Convenience and flexibility - Time savings	- Re-investing - significant underestimation possible in terms of the costs of running such solutions

Fig. 5. Analysis summary of the seven configurations using the REF [20].

In the first configuration, a synergy can be observed between the product-oriented PSS and the two CE strategies, as they are mutually reinforced. Preventive maintenance and repair can positively impact the product's efficiency in operation both with respect to energy use and more effective uptime in terms of performance and quality of the product's output. Further, the consolidated analysis using the REF highlights the interrelationships of possible RE and helps to identify triggers, drivers and mechanisms as the most important aspects of RE. The most prominent triggers were connected to the overall goal of a configuration considering both PSS type and the selected CE strategies, i.e., increase in resource efficiency and decrease in energy use. Further, the possible drivers explain how those triggers are driven to a certain mechanism contributing to overall RE (e.g., increase in profit, increase in interactions with customers, easier access to spare parts). Considering the mentioned triggers and drivers, possible mechanisms occurring can be noted as output mechanisms where the company can sell more spare parts when they are not actually needed to increase profit, due to e.g., more frequent interactions with a customer. This mechanism can be mapped as a causal loop which feedbacks back to the overall goal and possibly reduces the intended resource efficiency and/or increases the energy use.

6. Discussion

The use of the Framework for analysing the relationship of CE strategies and PSS types, the BESST and REF in a sequence provided a relatively quick but exhaustive way to formulate different configurations and analyse their impacts (benefits and costs), synergies, and RE already in the early stages of design for the case company. Given that a method to do such an analysis has not been found in the extant literature, and was needed by the industry, the authors believe that an important knowledge gap has been bridged by this proposal. The identification of the benefit and cost drivers and gauging of their significance is the first step towards a decision to select configurations to develop further, as it can help in painting a clearer picture of their TBL impact. A manufacturing company can, according to the above analysis, consider ways to further strengthen the identified synergies and mitigate RE. In the example of the first configuration, both can be achieved with a careful definition of the maintenance contract, by detailing the specific actions and responsibilities of both parties targeted to achieving e.g., greater energy efficiency. In that way, more clarity can be achieved concerning the influence of individual actions that service technicians execute during a service visit, and greater transparency can be ensured with respect to spare parts sales.

Based on the application of the BESST and REF, the first three configurations have a solid short-term TBL potential and a clearer picture of their mainly direct RE. Configurations 5 and 7, in turn, are considered to have the greatest long-term TBL potential. However, those are also the riskiest configurations due to the uncertainty of the impact of their primarily indirect RE, which are not researched well enough in the literature.

7. Conclusion

Rather than applying CE strategies individually, manufacturing companies have a much better chance of increasing their TBL sustainability and building resilience by combining them and studying their influence systemically since the early stages of design. Relatively meagre research exists to explore the impacts, synergies, and RE of such combinations, which is primarily focused on a hindsight analysis. This research proposes the application of the BESST and REF for an ex-ante analysis of seven configurations that include different PSS types and CE strategies in a single manufacturing company. The analysis provides a quick but exhaustive insight into benefit and cost drivers for each of the configurations, as well as their synergies and RE that can serve manufacturing companies as a support for decision-making and RE mitigation.

The study is limited to a single case capital goods manufacturing company operating in the business-to-business segment, thus hindering generalisable conclusions. The selection of CE strategies was also narrowed down in the initial selection, thus leaving out some strategies from the investigation ('refuse', 'recycle', and 'recover').

Further research includes the application of the BESST and REF in more cases, to be able to draw more general conclusions. Additionally, it should be investigated which configurations can go well together so that the manufacturers can provide a whole portfolio of configurations to customers at the lowest cost and the highest benefit because of their synergies and avoided RE.

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