THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Sustainability-as-a-Service: Advancing digital servitization for industrial sustainability

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The image includes an abstract representation of Sustainability-as-a-Service, where a pair of hands are offering digital services. Figure adapted from an illustration from freepik.com.

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ABSTRACT

The expectations and requirements of companies in today's world are higher than ever. With the increased urgency of achieving long-term sustainability, companies are increasingly exploring new business models that combine increasing digital capabilities with reaching sustainability objectives. And they are doing so from an economic, environmental and social perspective. Digital servitization is an excellent alternative with which to explore and expand offerings portfolios and connect entire value chains. Furthermore, sustainability can be conceptualised as a main source of value. Therefore, this thesis proposes the advancement of the term "Sustainability-as-a-Service".

This thesis presents six studies, mostly based on data from case studies conducted in different industrial sectors and exploring the challenges faced in adopting digital servitization models. The challenges presented cover economic, technical, organisational, contextual and support-related factors, which were identified across the theoretical and empirical findings. From an economic perspective, they reflect concerns about shifting responsibilities when servitizing and a lack of understanding of the value of data. From a technical perspective, recurrent challenges included varying levels of digital maturity across value chains and technology adoption in companies whose products have long lifecycles. From an organisational perspective, the risk-aversion perceived in some industries seems to hinder openness towards data sharing. Regarding contextual factors, existing regulations and a lack of standardisation limit the interoperability of systems required for digital servitization. Lastly, there is an apparent lack of support (such as frameworks and methods) that successfully integrates sustainability at the core of the value proposition for digital servitization.

This research also generates a list of requirements for Sustainability-as-a-Service. These requirements are categorised in a proposed framework, which includes: (i) value chain, (ii) company, (iii) overarching elements, including external factors, technology enablers and organisational skills and (iv) considered stakeholders. These dimensions include the actions proposed for industrial transitions towards Sustainability-as-a-Service. Finally, the proposed framework is evaluated empirically to establish the validity of its theoretical and practical contributions.

The outcomes of this research advance theory by identifying the challenges and requirements at the intersection of sustainability, servitization and digitalization. Furthermore, it can support industrial practitioners as they advance towards Sustainability-as-a-Service and move towards the vision of a sustainable industry in which value is decoupled from tangible assets.

Keywords: sustainability-as-a-service; digital servitization; sustainability; case studies

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Many say that “it takes a village to raise a child”. I was not a child when I moved to Sweden to become a PhD student, but I definitely had a whole village supporting my most formative years to date; a village that knew no geographical borders or time zones.

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To the colleagues and friends that Chalmers has given me, you have made my time on the fifth floor, a period of joy and growth – Camilla, Xiaoxia, Arpita, Adriana, Maja, Omkar, Hao, Ebru, Anders and everyone else who contributed to the friendly environment at Production Systems. Kate, thank you for your incredible support during my moving to Sweden. Greta, my office roommate, and best friend, thank you for becoming the sister I needed in life; you and your family are a key reason of why Sweden feels like home. Kornelia, thank you for making the hard times feel so much easier.

To my family, thank you for your love, patience, encouragement, and reassurance; you have believed in my dreams and goals even when I had doubts. Dad, you use every chance to remind me of my childhood dream of becoming “*una gran científica”*, thank you for always being there and for shifting the question from “why did this happen to me?”, to “what is this happening for?”. Mom, thank you for lovingly teaching me to study and to believe in myself. Some of my happiest childhood memories are of you practicing with me for spelling bee contests and preparing mock exams much harder than anything I ever faced at school. Thank you for making it your mission that all my dreams come true. To Jesus, my brother, thank you for being you, I can’t think of anyone else I would rather share books, thoughts, and life.

Finally, thank you to everyone involved in this journey during which I endeavoured to learn the craft of research, but where I also had a five-year adventure which I would have never dared to dream of.

Clarissa A. González Chávez

Gothenburg, 2023

LIST OF APPENDED PAPERS

The five appended papers are listed below, including the contributions of the authors.

Paper 1	**State-of-the-art on Product-Service Systems and Digital Technologies** **Clarissa A. González Chávez**, Mélanie Despeisse, and Björn Johansson (2021) Presented at the International Symposium on Environmentally Conscious Design and Inverse Manufacturing (EcoDesign 2019), Yokohama, Japan, 25-27 November 2019. Published in EcoDesign and Sustainability I. Sustainable Production, Life Cycle Engineering and Management, Springer Singapore, pp. 71-88. https://doi.org/10.1007/978-981-15-6779-7_6 *Clarissa conducted the literature review and wrote the first draft. The co-authors contributed to the planning process and keyword selection and supported with reviewing and editing.*
Paper 2	**Achieving Circular and Efficient Production Systems: Emerging Challenges from Industrial Cases** Mélanie Despeisse, Arpita Chari, **Clarissa A. González Chávez**, Xiaoxia Chen, Björn Johansson, Víctor Igelmo Garcia, Anna Syberfeldt, Tarek Abdulfatah & Alexey Polukeev (2021) Presented at International Conference on Advances in Production Management Systems (APMS 2021), Nantes, France, 5–9 September 2021. Published in: Dolgui, A., Bernard, A., Lemoine, D., von Cieminski, G., Romero, D. (eds) Advances in Production Management Systems. Artificial Intelligence for Sustainable and Resilient Production Systems. APMS 2021. IFIP Advances in Information and Communication Technology, vol 633. Springer, Cham. https://doi.org/10.1007/978-3-030-85910-7_55 *Clarissa led and designed the research activities of Pilot 1, where she conducted the data collection, conceptualised the case study, conducted the data analysis, and documentation. Clarissa also contributed by reviewing and editing the final draft.*
Paper 3	**Advancing sustainability through digital servitization: An exploratory study in the maritime shipping industry** **Clarissa A. González Chavez**, Selma Brynolf, Mélanie Despeisse, Björn Johansson, Anna Öhrwall Rönnback, Jonathan Rösler, and Johan Stahre (forthcoming) Submitted to Journal of Cleaner Production on the 18th of November 2023, first submission on 24th of April 2023 (Under review) *Clarissa conducted the literature review. With Selma, Clarissa planned and performed the workshop, company visits and the interviews from Companies A-G. She also performed the analysis of the full data set and wrote the initial draft. The co-authors provided additional data, and supported by providing feedback, visualizations, reviewing and editing.*

Paper 4	**Analyzing the risks of digital servitization in the machine tool industry** **Clarissa A. González Chávez**, Gorka Unamuno, Mélanie Despeisse, Björn Johansson, David Romero, Johan Stahre (2023) Published in Robots and Computer-Integrated Manufacturing Volume 82, art. no. 102520. https://doi.org/10.1016/j.rcim.2022.102520 *Clarissa conceptualized the research study. With Gorka, Clarissa planned the study, analysed the data, and developed a first draft. With Mélanie, Clarissa developed the recommendations based on the risk analysis. The co-authors supported by providing feedback, reviewing and editing.*
Paper 5	**Sustainability-as-a-Service: Requirements Based on Lessons Learned from Empirical Studies** **Clarissa A. González Chávez**, Mélanie Despeisse, Björn Johansson, David Romero and Johan Stahre Presented at the International Conference on Advances in Production Management Systems (APMS 2023), Trondheim, Norway, 17-21 September 2023. Published in: Alfnes, E., Romsdal, A., Strandhagen, J.O., von Cieminski, G., Romero, D. (eds) Advances in Production Management Systems. Production Management Systems for Responsible Manufacturing, Service, and Logistics Futures. APMS 2023. IFIP Advances in Information and Communication Technology, vol 690. Springer, Cham. https://doi.org/10.1007/978-3-031-43666-6_13 *Clarissa performed the literature review, analysed the data and built the framework based on cross-case analysis of previously conducted studies. The co-authors supported by reviewing and editing the final draft.*

LIST OF ADDITIONAL PAPERS

This section presents a list of additional publications that, related work important for this thesis but outside the scope of the research questions. This section describes how the articles contributed to the research enquiry.

Paper I	**Circular Lean Product-Service Systems Design: A Literature Review, Framework Proposal and Case Studies** **Clarissa A. González Chávez**, David Romero, Monica Rossi, Rossella Luglietti, Björn Johansson (2019) Presented at the 11th CIRP Conference on Industrial Product-Service Systems, Zhuhai and Hong Kong, 29-31 May. Published in Procedia CIRP 83 (2019): 419-424. https://doi.org/10.1016/j.procir.2019.03.10 *Clarissa and David planned the study. Clarissa conducted the data collection, and analysis and wrote the first draft. The co-authors supported by supervising the Master's thesis, reviewing and editing.*
Paper II	**Could Circular Business Models provide a Solution for E-waste? Insights from a Refrigerator Recycling Company.** **Clarissa A. González Chávez**, Doroteya Vladirimova, Mélanie Despeisse, Björn Johansson, Henrik Jilvero and Steve Evans. Presented at the International Conference of New Business Models 2019, Berlin, Germany, 1-3 July 2019 Published in Lüdeke-Freund, F. & Froese, T. (2019): Proceedings of the 4th International Conference on New Business Models: New Business Models for Sustainable Entrepreneurship, Innovation, and Transformation, Berlin, Germany, 1-3 July 2019. Berlin: ESCP Europe. ISBN 978-3-96705-001-1 *Clarissa planned the study, conducted the data collection, analysis and wrote the first draft. The co-authors reviewed and edited the draft.*
Paper III	**Finding and Capturing Value in e-Waste for Refrigerators Manufacturers and Recyclers** **Clarissa A. González Chávez**, Mélanie Despeisse, Björn Johansson, David Romero (2020) Presented at International Conference on Advances in Production Management Systems 2020 (online) Published in Lalic, B., Majstorovic, V., Marjanovic, U., von Cieminski, G., Romero, D. (eds) Advances in Production Management Systems. The Path to Digital Transformation and Innovation of Production Management Systems. APMS 2020. IFIP Advances in Information and Communication Technology, vol 591. Springer, Cham. https://doi.org/10.1007/978-3-030-57993-7_57 *Clarissa planned and conducted the literature review and wrote the first draft. The co-authors supported by reviewing and editing.*

Paper IV	**Towards sustainable servitization: A literature review of methods and frameworks** **Clarissa A. González Chávez**, Maria Holgado, Anna Öhrwall Rönnbäck, Mélanie Despeisse, Björn Johansson (2021) Presented at CIRP International Conference on Manufacturing Systems 2021 (online) https://doi.org/10.1016/j.procir.2021.11.048 *Clarissa planned the literature review and defined the categories of analysis with Maria. Clarissa conducted the literature review and wrote the first draft. The co-authors supported by reviewing and editing.*
Paper V	**The role of TRUST in service-based business models: The case of the fashion industry** **Clarissa A. González Chávez**, Doroteya Vladimirova, Laetitia Forst, Mélanie Despeisse and Björn Johansson (2022) Presented at International Conference on New Business Models 2022, Rome, Italy, 22-25 June 2022 Published in: Michelini L., Minà A and Alaimo Di Loro P. (eds), (2022). Proceedings of the 7th International Conference on New Business Models: Sustainable Business Model Challenges: Economic Recovery and Digital Transformation, LUMSA University. ISBN 979-12-210-1188-3 *Clarissa and Doroteya conceptualised the study as part of an online research exchange. Clarissa conducted the literature review and developed the first draft. The co-authors supported by reviewing and editing.*
Paper VI	**A systematic review of empirical studies on green manufacturing: eight propositions and a research framework for digitalized sustainable manufacturing** Mélanie Despeisse, Arpita Chari, **Clarissa A. González Chávez**, Helena Monteiro, Carla Gonçalves Machado, Björn Johansson (2022) Published in Production & Manufacturing Research, 10:1, 727-759. https://doi.org/10.1080/21693277.2022.2127428 *With her co-authors, Clarissa contributed to the planning of the study. Clarissa also partially conducted the literature review and contributed by being part of the analysis, reviewing and editing*
Paper VII	**Achieving Sustainable Manufacturing by Embedding Sustainability KPIs in Digital Twins** **Clarissa A. González Chávez**, Maja Bärring, Marcus Frantzén, Arpita Annepavar, Danush Gopalakrishnan, Björn Johansson (2022) Presented at 2022 Winter Simulation Conference (WSC) in Singapore, 11-14 December. https://doi.org/10.1109/WSC57314.2022.10015336 *Clarissa and Marcus designed the study and supervised the Master's thesis. Clarissa and Maja wrote the draft of the article based on the Master's thesis by Arpita and Danush. The co-authors supported by reviewing and editing.*

Paper VIII	**Battery production systems: state of the art and future developments** Mélanie Despeisse, Björn Johansson, Jon Bokrantz, Greta Braun, Arpita Chari, Xiaoxia Chen, Qi Fang, **Clarissa A. González Chávez**, Anders Skoogh, Johan Stahre, Ninan Theradapuzha Mathew, Ebru Turanoglu Bekar, Hao Wang, Roland Örtengren (2023) Presented at the International Conference on Advances in Production Management Systems (APMS 2023), Trondheim, Norway, 17-21 September 2023. Published in: Alfnes, E., Romsdal, A., Strandhagen, J.O., von Cieminski, G., Romero, D. (eds) Advances in Production Management Systems. Production Management Systems for Responsible Manufacturing, Service, and Logistics Futures. APMS 2023. IFIP Advances in Information and Communication Technology, vol 690. Springer, Cham. https://doi.org/10.1007/978-3-031-43688-8_36 *Clarissa wrote the subsection on service-based business models and supported by reviewing and editing.*
Paper IX	**Using digital platforms for value chain sustainability – Cases from the Digitala Stambanan project** **Clarissa A. González Chávez**, Arpita Chari, Adriana Ito, Maja Bärring, Martin Friis, Magnus Mörstram, Paulo Victor Lopes, Johan Stahre Presented at the CIRP Conference on Manufacturing Systems (CIRP CMS 2023), Cape Town, South Africa, 24 - 26 October 2023 Publication in Procedia CIRP forthcoming. *Clarissa and Arpita conducted the literature review and wrote the first draft. Clarissa led and documented the research work of Value Chain 3. The co-authors supported by reviewing and editing.*

Paper I provided a transition for the research between the Master's studies and the PhD journey. Papers II and III documented a pre-study and led to the results of Paper 2. Paper IV provided a foundation for the development of the framework proposed in Paper 5. It does so by indicating gaps in the existing support methods, tools and frameworks for servitization. Paper V explored the role of trust in servitization in the fashion context; its findings were included in the development of Paper 5. Paper VI clarified the gap in manufacturing research connected to servitization regarding sustainability. Paper VII allowed the exploration of a technical perspective on digital services and was part of the pre-study for Paper 4. Paper VIII enabled the conceptual exploration of servitization in the context of battery production and provided a further multi-author collaborative experience. Paper IX explored the possibility of future research based on the development of digital services delivered through platforms, by exploring their potential for value chain sustainability in Swedish industry.

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LIST OF ABBREVIATIONS

AI – Artificial Intelligence

AR – Augmented Reality

CE – Circular Economy

DPSIR – Driver, Pressure, State, Impact, Response

DRM – Design Research Methodology

ERP – Enterprise Resource Planning

GDP – Gross Product Growth

IoT – Internet of Things

IT – Information Technology

MES – Manufacturing Execution System

PESTEL – acronym for: Political, Economic, Social, Technological, Environment and Legal

PSS – Product-Service Systems

SDGs – Sustainable Development Goals

TBL – Triple Bottom Line

UN – United Nations

VR – Virtual Reality

WEEE – Waste from Electrical and Electronic Equipment

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"'If you have knowledge, let others light their candles in it.'"

– Margaret Fuller

INTRODUCTION

This chapter presents the background of the thesis, introducing the paradigm of Sustainability-as-a-Service. Further, it explains the main motivation to undertake this research journey and describes the defined vision, aim, research questions and scope.

1.1 BACKGROUND

Throughout history, businesses have continuously reorganised through eras of growth, stagnation, stability and crisis (Goldstone, 2002). The commercialisation of products and services has unavoidably revolved around the covering and fulfilment of societal demands (Fel'd, 1970). The industrial revolutions have drastically changed economic models, where the achievement of increased productivity paved the way for an unsustainable linear economy.

Industrial focus on services have changed through time, though since the mid-nineteenth century Ford claimed that "a manufacturer is not through with his customer when a sale is completed" (Crowther & Ford, 1924). His statement inferred the need for after-sales services such as repair. The notion of services and the shift in strategies required by this concept have highlighted opportunities to decouple value capture from physical products (Thomas, 1978).

Today, the rapid growth of digitalisation and growing competition have made gaining a competitive advantage a bigger challenge, with no room for services as an afterthought (Lindhult et al., 2018). This notion has been well-known to managers since the 1990s, when market saturation opened the way to increased need for non-tangible value in companies (Vandermerwe, 1993). Previously prevalent product-centric business models regularly prove insufficient when it comes to capturing business value and retaining competitive advantage (Slywotzky et al., 2003).

The concept of servitization has gained momentum as studies highlight its potential for increased competitive advantage and sustainability benefits (Vandermerwe & Erixon, 2023). The sustainability consideration is highlighted by emphasizing value propositions based on solutions (Tukker, 2015), such as supplying lights rather than selling lightbulbs (Phipps, 2018). Consequently, servitization as a transition from product-centred to service-based company models is well characterized by many industrial enthusiasts who inspired by Rolls-Royce, Kone, Caterpillar, and others, perceive a high potential for long-term industrial success (Kohtamäki, Parida, et al., 2020).

In Sweden, the last 20 years have seen a rapid increase in the role of services for the Swedish economy (Kohtamäki et al., 2021). The production of services and their constant prices have more than doubled. In 2000, service production accounted for 60% of the value added from the business sector, and in 2020 this number increased to almost 68% (Almega, 2022). The increased relevance of services to the national economy is not a new phenomenon but has been strengthened by the appearance of new technologies and innovations. Combined with the increasing ecosystems and global platforms, these are accelerating the service revolution. Although already identified as a trend (Fournier & Axelsson, 1993), recent data on the influence of the service sector on increased employment and its substantial contribution of this sector to the countries' GDP (*World Development Indicators*, 2023), adds credence to it being perceived as a necessary step towards more sustainable industry.

Undeniably, the environment has been one of the most impacted stakeholders from our society's expanding consumption and production practices. The depletion of natural resources and environmental pollution has created decades of environmental degradation that prompt calls for immediate action (Evans et al., 2017; Han et al., 2020). By 2030, it is anticipated that water, food and energy requirements will increase by 40%, 35% and 50% respectively in comparison with 2017 levels (*Global Wealth Report*, 2019; Voulvoulis, 2022). To address this, increased control have been proposed in recent years by regulating organisations and governmental authorities (*A European Green Deal: Striving to be the first climate-neutral continent*, 2020). These initiatives aim to bring awareness about the unsustainable nature of the linear economy, also referred to as business-as-usual (Acheampong & Opoku, 2023).

Companies, as problem solvers, have enormous potential to facilitate the shift to more sustainable business models and potentially help change previously linear patterns of production and consumption (Lüdeke-Freund et al., 2022). Therefore, sustainability must be considered a primary need for every product and service in the market (Kristensen & Remmen, 2019). Engaging in increasingly sustainable products and services can benefit from taking a Triple Bottom Line (TBL) perspective, where sustainability is only achieved when the three pillars (environmental, social and economic) are addressed (Elkington, 1997). However, engaging in the sustainability is still an afterthought for many companies, where a more proactive role is required to successfully engage in this transition (Garetti & Taisch, 2012; Mio et al., 2020). Today, some of the vision statements of large manufacturing companies have begun to reflect their desire to influence and change consumer habits (WBCSD, 2017). Such a transition might be happening partly in response to the rising urgency to contribute to the Sustainable Development Agenda, featuring the MDGs, the 2030 Agenda and the Paris Agreement (Mio et al., 2020; UNCTAD, 2020). However, it is undeniable that making sustainability a priority is also a survival factor, given the economic challenges that go with tackling climate change (Wolff et al., 2020).

Servitization is a concept on the rise and it describes the transformation of companies which convert their primary offerings from a tangible products to ones that includes intangible services (Vandermerwe & Rada, 1988). Other related concepts have emerged over the years, such as the idea of Product-Service Systems (PSS) (Tukker, 2004); this reflects the addition of intangible services to a tangible product to extend lifecycles and enhance income streams (Reim et al., 2015). Embedding sustainability outcomes in PSS has been approached by embedding circular economy principles into the business model, and thus re-using and remanufacturing (among other strategies) could be used to upgrade cycles and improve performance overtime through disruptive business propositions (Copani & Behnam, 2020).

Digitalization reflects the increased availability, use and maturity of digital technologies in industry, and has highlighted opportunities and challenges for companies (Coreynen et al., 2017). When it comes to deploying servitization, digitization is a game changer for businesses to identify, capture, and deliver value from their customers (Vendrell-Herrero et al., 2017). As a result, digital servitization has become more prevalent in management and engineering literature over the previous decade. There are numerous arguments as to which term drives the other (Zhou et al., 2021). Most authors, agree that this symbiotic relationship is most effective when the terms are integrated, as they are reinforced via feedback loops between digital capabilities and service-based, business model thinking (Luz Martín-Peña et al., 2018).

To date, the topic of digital servitization represents an evolution from the traditional servitization research field, in that digital servitization takes advantage of the increased availability of digital technologies (Dalenogare et al., 2023; Kohtamäki, Parida, et al., 2020). However, the extent to which this business model can support industrial sustainability represents a gap in the literature and industrial advancement (Schiavone et al., 2022). Some researchers have looked at this intersection from the perspectives of the potential for digital technologies to enable a circular economy within service-based business models, (Bressanelli et al., 2018b), the capabilities required (Hallstedt et al., 2020; Marcon et al., 2022), digitalization (Pirola et al., 2020), impact on sustainability paradoxes (Brax, 2005; Gebauer et al., 2005; Opazo-Basáez et al., 2018; Paiola et al., 2021; Tóth et al., 2022), and quantitative analysis (Coreynen et al., 2020; Neely, 2008).

In the last years, there has been a rapid rise in the concept of as-a-service models, where the delivery of solutions (e.g. software-as-a-service, platform-as-a-service) have rapidly expanded across industrial sectors, further developing the concept of digital servitization (Park, 2022). However, there is still room to explore how this topic can be advanced and embed sustainability

by learning from the current state of practice and developing new theories.

This work identifies the trends of servitization, sustainability and digitalization and, in their intersection identifies a real-world and research problem. Despite the growing research and industrial interest, digital servitization remains poorly disseminated in many industrial sectors, which struggle to separate their main sources of value from material offerings. Furthermore, there is an even larger gap in the potential connection of such studies with a sustainability perspective. The present research advances the understanding of digital servitization for sustainability by investigating current challenges and opportunities and identifying recurrent dimensions of change to understand what companies require in order to develop digital servitization centred on the concept of sustainability (referred to this paradigm as "Sustainability-as-a-Service").

1.2 VISION, AIM AND RESEARCH QUESTIONS

My vision is an industry that successfully decouples sustainable value from tangible assets. To move towards the vision, the aim of this thesis is to identify the challenges in the industrial adoption of digital servitization, along with understanding what is required from companies to engage in digital servitization with sustainability at the core.

This work addresses the existing knowledge gap at the intersection of servitization, digitalization and sustainability. The gap has been documented in a few empirical cases and stems from the lack of guidelines and support tools for companies to exploit this conceptual intersection. The work proposes a first research question which identifies the challenges of digital servitization for sustainability from a theoretical and practical perspective.

RQ1) What are the challenges of digital servitization for sustainability?

Furthermore, the challenges identified lead to the primary need to establish requirements from industry to successfully develop Sustainability-as-a-service and support a transition towards more a sustainable industry. This is explored in the second proposed research question:

RQ2) What are the requirements for Sustainability-as-a-Service?

These research questions have guided the work presented in this thesis. Firstly, given that problem-solving is a process, understanding the challenges is a suitable first step. This can be undertaken by organising problems often initially represented as a swamp (Bennett, 1989). The second research question positions Sustainability-as-a-Service as a paradigm for sustainability is at the core of digital servitization. This represents a complex transition for companies and value chains. The selection of the word “requirement” refers to a term that “encompasses all aspects of system prior to actual system design” (Ross & Schoman, 1977). From a theoretical and empirical perspective, this allows knowledge to advance.

1.3 SCOPE AND DELIMITATIONS

This thesis takes an exploratory approach, suggesting the possibility of adopting digital servitization for one or more offerings from an industrial company at an experimental level. This research has been conducted under a mix of international and national projects. The companies were mainly located in Sweden and Northern Europe. Also, this research has chosen to engage with several industrial sectors. This has afforded an understanding of a broader state of practice that missing in current literature. The transferability of results to other regions and industrial sectors is expected, though the geographical scope of the studies is acknowledged. Although this research bases its definition of sustainability in the TBL, the intent of its studies was not to extract findings connected solely to social sustainability.

1.4 STRUCTURE OF THE THESIS

This thesis is structured into the following chapters:

Chapter 2, Frame of reference introduces the concepts and theories required to position this research.

Chapter 3, Research methodology, unpacks the research journey followed to design, execute and synthesise the findings of this thesis.

Chapter 4, Results, recapitulates the five appended papers, which are key to answering the research questions. Additional findings are included for Study F, as they help this research to achieve its aim.

Chapter 5, Discussion, presents an interpretation of the results by answering the research questions. It describes the contribution of this research work, reflects on the methodological limitations, and offers suggestions for the future advancement of this research.

Chapter 6, Conclusions, offers a synthesis of the main findings and their conclusions.

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"Nothing in life is to be feared, it is only to be understood."

– Maria Salomea Skłodowska

FRAME OF REFERENCE

This chapter presents the frame of reference relevant for this thesis its two research questions. The chapter begins by presenting the industrial revolutions and the urgency in industrial agendas to achieve sustainability through suitable business models, particularly digital servitization. Furthermore, it presents the role of digitalization in servitization, and describes digital servitization. It then discusses the role of digital servitization for sustainability.

2.1 INDUSTRIAL SUSTAINABLE DEVELOPMENT

This subsection introduces the historical background for the current industrial scenario and provides the frame for the use of sustainability theories in the development of servitization.

2.1.1 Industrial revolutions

The First Industrial Revolution (1760-1860), characterised by the steam engine, spinning jenny and iron-making, brought new working methods, increases in industrial production and everyday consumption and saw the beginning of a long urbanisation journey (Gray, 1984). The Second Industrial Revolution (1870-1914) emphasised the importance of societal structures, witnessed the growth of cities and saw people's lives become regulated by the clock rather than the sun. Mass production, or "Fordism", as it was often known, was a stamp of this era which brought together previous manufacturing practices and supported price reductions through economies of scale (Freeman, 2018). This era saw an improved economy, with individuals gaining increased purchasing power (Vandermerwe, 1993). Productivity (measured by per-hour output) and mass production increased the affordability of what were once considered luxury products and paved the way for a linear economy (Atkeson & Kehoe, 2001; Cooper, 1999).

Later, the post-war period, or the Glorious Thirty (years) in France (1945-1975), when the GDP per capita saw its biggest boom, giving birth to a consumer society and creating a phenomenon of rapid growth in many recovering countries (Jorgenson, 1988; Maclean, 2002). The changing economy created societal phenomena that paved the way for a linear economy, driven by a mindset in which increasing product availability decreased perceived value (Cooper, 1999). Then, the Third Industrial Revolution (1970s) began with the accelerated uptake of electronics and communication technologies. Today, it must be acknowledged that technology is the backbone of commerce and industry as we know it (Carr, 2003).

Industry 4.0, a term coined in 2011, refers to "a new industrial maturity stage of product firms, based on the connectivity provided by the industrial Internet of things, where the companies' products and process are interconnected and integrated to achieve higher value for both customers and the companies' internal processes" (Frank et al., 2019, p. 343). This industrial paradigm has transformed the landscape for businesses and markets by offering increased possibilities to monitor, optimize and automize product and services lifecycles (Liao et al., 2017). The technologies embedded in Industry 4.0 have been a core driver to the radical transformation experienced in both processes and business models, opening the door for digital servitization.

In 2021, Industry 5.0 was brought to light. The European Commission published a report which exposes the global industrial transformation and brings light to the need for a human-centric approach in manufacturing systems (European Commission et al., 2021). This concept proposes an era of socially intelligent factories based on three main pillars: human centricity, sustainability, and resilience (Maddikunta et al., 2022). Some discussions around this term stem from the need for a buffer period between industrial revolutions. However, the societal and environmental focus of Industry 5.0 highlights the need for a process in industrial history which harmonizes machines, humans, values, tasks, knowledge, and skills resulting in more sustainable and personalized products and services (Leng et al., 2022).

2.1.2 Sustainable Development

Industry is increasingly concerned with addressing the undeniable environmental urgency. A transition towards more sustainable practices is unquestionably impacting industry's strategical and managerial perspective and creating a new competitive framework for

companies (Werbach, 2011). This has expanded to the production and manufacturing domains (Herrmann et al., 2014). Business-as-usual, aligned with an implausible linear economy, is increasingly subjected to rethinking, restructuring, and redesigning towards a more sustainable future (Acheampong & Opoku, 2023). Therefore, recent decades have seen researchers and practitioners jointly examining how companies can operate whilst striving for success and contributing to sustainability (Paramanathan et al., 2004).

This research identifies sustainability using the definition proposed by Elkington (1997) that includes the TBL in which sustainability is only achieved when all three pillars are addressed. In 2015, the United Nations' Sustainable Development Goals (SDGs) (United Nations, 2015), adopted by 193 countries that belong to the UN General Assembly. Since then, the SDGs have taken on the mantle of lodestar for organisations whose mission is to establish better priorities and working guidelines to support a more sustainable planet (WBCSD, 2017).

Sustainable development is a recurrent concept describing the conditions for desirable societal development (Mio et al., 2020). This research identifies with the definition from the report "Our Common Future", published in Harlem (1987) which states that, "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs". This definition comprises two key concepts:

- the concept of "needs", in particular the essential needs of the world's poor, to which overriding priority should be given; and
- the idea of limitations imposed by the state of technology and social organisation on the environment's ability to meet current and future needs.

Embedded in the proposed definition of sustainable development is the fact that systems must be sustainable in the long term (Kristensen & Remmen, 2019). Therefore, we need to adapt industrial behaviour and consumption patterns to meet the requirements of our global priorities (Coffay & Bocken, 2023). To make this possible, organisations need to adjust their current ways of working, transforming them into a natural prioritisation that identifies valuable sustainable sources and matching business models (Evans et al., 2017; Hölscher et al., 2018).

The concept of "business models" was first addressed in the literature in 1957 (Bellman et al., 1957) and has continued to court controversy across disciplines, due to significantly varying elements among existing definitions. For instance, some have defined business models as structured management tools that are considered especially relevant to success (Magretta, 2002). Alternatively, some researchers identify business models as key enablers of businesses, fundamentally concerned with creating value and capturing returns (Zott & Amit, 2010). Thus, in simple terms, a business model may be defined as "a representation of reality" (Shafer et al., 2005).

Industry's predominant business model has spread to manufacturing (Wei et al., 2017), and its still, to some extent, reflecting perceived unlimited resources and unlimited regenerative capacity. (Garetti & Taisch, 2012). This erroneous perception is in urgent need for a transformation. Businesses have the potential to create more sustainable value, as industrial development is largely responsible for the environmental challenges that society is facing. But they also have knowledge, skills and resources which are the key to solving such challenges (Lüdeke-Freund et al., 2022). Recent decades have highlighted the potential for business models to decouple from the industrial-age ideas of mass consumption and production and instead embed sustainability principles and thus create sustainable value (Bocken et al., 2014; Coffay & Bocken, 2023). This way of using businesses as an engine for innovation has been called "sustainable business models" (Lozano, 2018).

Creating sustainable business models centred on sustainable value requires the rethinking and redesign of business-as-usual (Evans et al., 2017). Some of the opportunities that arise through this transition include new means of differentiation, growth-orientated benefits and new business opportunities for manufacturing companies (Valkokari et al., 2014). In a sustainable industry supported by sustainable business models, conceptualisation and prioritisation of value is highly dynamic (Osterwalder & Pigneur, 2010; Vladimirova, 2019). As a result, companies face the undeniably complex challenge of understanding what type of value their customers expect. This is highly necessary for the development of sustainable business models (Sakao et al., 2013). Failing to understand, capture and deliver value means failing to succeed.

2.2 SERVITIZATION AS MEANS FOR ACHIEVING SUSTAINABILITY

Various consumption schemes have been proposed in recent decades to retain competitiveness while decreasing environmental impact. As a result, the concepts of sustainable business models (Stubbs & Cocklin, 2008), environmental assessments (Morgan, 2012), dematerialisation (Bartelmus, 2003), product-service systems (Mont, 2000) and servitization (Vandermerwe & Rada, 1988) have emerged as popular fields in literature, as well as a recurring topic among practitioners.

As a concept, servitization embodies the proposal that finding value in service-centred offerings instead of product-centred ones brings many advantages (Neely, 2008). For instance, it creates firmer and closer relationships with customers, has more precise and potentially sustainable value propositions and becomes solution orientated (Baines et al., 2017). Moreover, one of the biggest opportunities foreseen in the transition to servitization, is the way that the circular economy principles can be embedded in business activities (Tukker, 2015).

2.2.1 Origins of servitization

Servitization, first introduced by Vandermerwe and Rada (1988) refers to solutions in which products and services are integrated (Baines et al., 2009). Examples include advanced data analytics and visualisation (Opresnik & Taisch, 2015), high-fidelity simulation and prediction, intelligent decision-making support and human-machine interaction (Chuang & Chen, 2022).

When discussing servitization, it is unavoidable to identify PSS, also defined as a Scandinavian concept that couples the debate on sustainability and reduction of environmental impact with shifting propositions aimed at increased service components (Baines et al., 2007). In their definition, Annarelli et al. (2016) suggest PSS as a market proposition focusing on the end-user's needs rather than the production process. PSS is considered a concrete response to pressures for a more sustainable society, which evolves from principles of innovation strategy to fulfil clients' demands (Cavalieri & Pezzotta, 2012; Tukker, 2004). This allows a need-fulfilment system with radically lower impact but enhanced environmental and social benefits (Reim et al., 2015).

PSS represents a field of research that is increasingly associated with prototyping and (Neely, 2008) design from an offering's perspective, while servitization is linked to an entire strategy to decouple the value of tangible products from organisations' success (Kim & Lee, 2021). The nature of the PSS concept and its relationship to early engineering design is justified by the crucial role of early stage engineering phase in enabling sustainability in the later lifecycle phases (Rondini et al., 2020). Furthermore, servitization requires the development of capabilities to systematically design and develop services (Rapaccini et al., 2013), as seen in Figure 1.

The transition from product-centred approaches to service-based ones has also been documented as "service-dominant logic" in the work of (Vargo & Lusch, 2004). This approach becomes increasingly relevant in the field of digital servitization, as the shift of mindset in organisations is identified as one of the biggest challenges (Kohtamäki, Einola, et al., 2020). Including a service-dominant logic in business model transformations can support the successful decoupling of value from material assets. It avoids shifting only revenue models without actually redefining value (Zhou et al., 2021).

In the 1980s the shift towards services was exemplified in the automotive sector (Mahut et al., 2017). In this period a transition towards consultative and relational roles was made tangible through account management and business-to-business (B2B) provision of services and solutions. The differences between B2B and business-to-consumer (B2C) approaches is significant, requiring to re-evaluating results and insights before attempting to generalize findings across these two concepts (Kreye & van Donk, 2021).

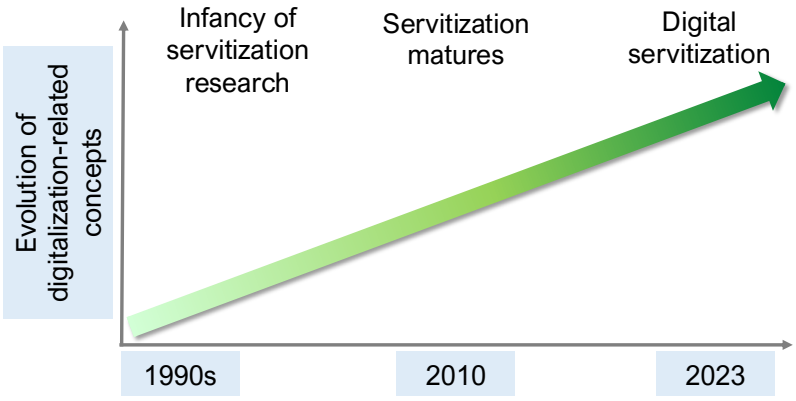

Figure 1. Evolution of digital servitization (Kohtamäki et al., 2022)

2.2.2 Impact of servitization on sustainability

Servitization has often been described as an enabler; a stepping-stone of industrial transition to sustainable development. It offers many advantages from a TBL perspective (Opazo-Basáez et al., 2018). The multidisciplinary characteristics of this business model have allowed it to be explored from multiple perspectives (Gaiardelli et al., 2021). Some studies address the role of servitization as a potentially useful tool for managing an economy in which resource efficiency is prioritised (Tukker, 2004, 2015) to such an extent that it leads to improved sustainability (Doni et al., 2019; Mont, 2004). The reasoning behind this perspective, is the perceived consistency perceived between service-based business models and the essence of the circular economy (Tukker, 2015).

Companies are increasingly considering expanding their offerings into services as a new way of generating additional revenue and profit. This increasing interest in services is leading companies to transition from a product-centred business model to a service-centred one (Gebauer et al., 2005). In a service-based business model, economic revenues are designed as an output of services (particularly digital ones), with companies encouraged and incentivised to extend both product and service lifecycles. Moreover, servitization improves customer-orientatedness (Lexutt, 2020). Firms with greater customer awareness are more likely to engage in sustainability practices, such as implementing sustainability standards in their supply chains (Zhang et al., 2022). The emergence of this increased interest is due in part to the high level of competition in many markets, the constant pressure for companies to be responsive and have faster communications and the decreased profit margins of products (Bustinza et al., 2015).

Servitization holds the potential to extend value from product-centred to service-centred offerings (Gebauer et al., 2005), such as creating firmer and tighter relationships with customers, having more precise value propositions and becoming solution-orientated. Rust and Ming-Hui (2014) state that, "the service revolution and the information revolution are two sides of the same coin", where servitization is considered a data-intensive transformation of the manufacturing industry (Opresnik & Taisch, 2015). Nevertheless, the way servitization enables the commercialisation of data and information has only been explored to a limited extent (Opresnik & Taisch, 2015). Few contributions address the use of sensor data in production systems to monitor units and develop sustainability-orientated services (Negri et al., 2017).

From a social perspective, servitization is believed to emphasise value co-creation with customers (Stoll et al., 2020). It motivates manufacturing firms to implement social sustainability practices, build good relationships with external stakeholders and thus improve their social performance (Zhang et al., 2022). As shown in Figure 2, Yang and Evans (2019) describe sustainable value propositions based on the archetypes of product-service systems (Tukker, 2004).

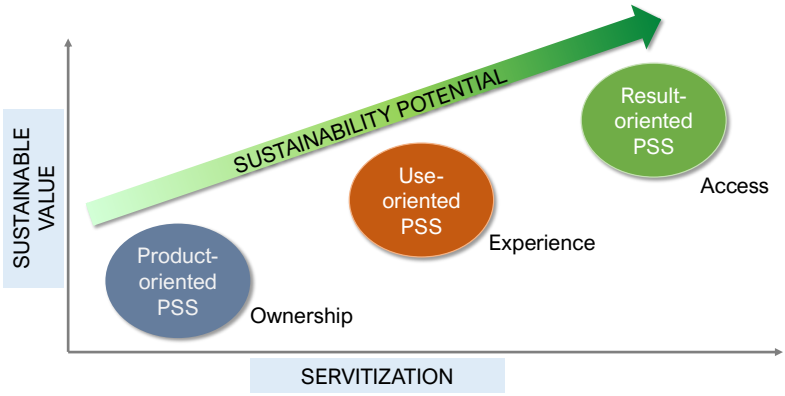

Figure 2. Servitization in relation to Sustainability
(Tukker, 2004; Yang & Evans, 2019)

2.2.3 Sustainability paradox of servitization

Although there are many reported potential advantages of PSS and servitization, it should be stated that PSS is not, by definition, a circular business model. However, studies have suggested that it might help organisations reach sustainability targets (Antikainen et al., 2018). Sustainability concerns have created a pull towards digitalized solutions which maximise the use of tangible resources through services (Schiavone et al., 2022). Some of the original definitions of PSS support this point by including dematerialization and reinforcing sustainability and competitiveness goals (Annarelli et al., 2016).

The shift in business models is often not a straightforward process, and often they can bring along unintended negative side-effects that companies fail to identify. In their work, Verboven and Vanherck (2016) address the potential sustainability paradox in the shift towards new business models, and propose a definition which highlights that there is a contradictory effect between the obvious effects of a sustainable business model, and the missed negative external factors, which can lead to rebound-effects not only on a systemic level, but also on customers behaviour. The sustainability paradox of servitization refers to cases in which the impact of company's sustainability worsens as it fails to adopt a suitable servitization strategy (Brax et al., 2021; Kohtamäki et al., 2018). This matter must be carefully monitored, as there are imminent risks in expanding on the paradox created by the lack of embedment of sustainability thinking, and proper follow up in servitization transitions (Argento et al., 2022).

2.3 DIGITAL SERVITIZATION FOR SUSTAINABILITY

This section presents how digitalization can be an enabler of servitization and support companies on their journey towards becoming more sustainable. It also presents the definition of digital servitization and conceptualises Sustainability-as-a-Service, as presented in this thesis work.

2.3.1 Digitalization as an enabler of servitization for sustainability

Digitalization refers to the digital representation of a product or service that allows easier delivery and manipulation of the value proposition (Bitner et al., 2010). *Digital technology* has emerged as an umbrella term which includes the tools used to achieve digitalization. For instance, the Internet of Things (IoT) was a term first coined by Ashton (2009) to describe the interconnection of physical objects through added sensors. IoT has impacted companies and become a vital element in the Fourth Industrial Revolution (Suppatvech et al., 2019).

The way that digitalization impacts entire business models cannot be ignored. Some researchers have used the term *digital business models* to refer to business management activities in a company's operations which incorporate digital technologies. Some of the most common are mobile devices, analytical analysis tools, sharing platforms and IoT (Luz Martín-Peña et al., 2018). The rapid development of solutions capable of simply collecting and managing data (Janković et al., 2022), has incentivised contributions addressing the use of sensor data in production systems to monitor units and develop sustainability-orientated services (Negri et al., 2017). Some authors have highlighted the lack of support available to companies as they integrate advanced services using digital technologies (West et al., 2021).

Evangelista et al. (2014) explain that the move towards a digital society is not about getting people to use technology but about its actual impact and how it transforms people's lives. Dealing with digitalization and assessing its socioeconomic impact requires comprehensive indicators which showcase the larger-scale economic and social impact (Strohmaier et al., 2019). A major challenge lies in organisational capabilities, such as configuring hardware components to sense and capture information (Lenka et al., 2017).

Based on the premise that a linear economy is not sustainable (Stahel, 2016), digitalization is undeniable an enabler of the transition towards more sustainable business models (George et al., 2021; Neu & Brown, 2005). It can be used to embed circular economy principles in value offerings (Foundation, 2015) among other things by: (1) extending the lifecycles of the products that are manufactured using non-renewable resources, (2) designing out waste and (3) regenerating natural systems, among others. Their integration of these principles as guidelines in the planning of future production systems for more sustainable manufacturing is both a theoretical and practical imperative (Acerbi et al., 2022).

Digitalization refers to increased data availability, accessibility, interoperability, connectivity and efficient data communication, computation and storage that allows easier delivery and manipulation of a product or service (Bitner et al., 2010; Liu et al., 2021). Furthermore, the concept of Industry 4.0 refers to a transformation in which sensors, machines, workpieces and IT systems (Rüßmann et al., 2015) enabled by Internet of Things (IoT) and cloud platforms, enable service-orientated, digitalized and sustainable business models that revolutionise complete value chains (Paiola et al., 2021). An example of the possible effects of such transformation lies in the way that lifecycle data results in the possibility of a more efficient, flexible and practical performance, covering precise customer needs (Bouncken et al., 2021; Xin & Ojanen, 2017).

Academia and industry currently attribute major opportunities to the emergence of *big data*, a term relating to the large volume of information and its variability, variety, velocity, veracity and value (Philip Chen & Zhang, 2014). The potential big data affords for developing new service-based business models is yet to be explored. However, digitalization and servitization must converge, as the combination of new technologies, connectivity and data analysis goes hand-in-hand with creating new value propositions. Doing this requires firms to cover the gap between the rapid speed of digital transformation and the pace of their adaptation process (Luz Martín-Peña et al., 2018).

Recent decades have shown that the rapid increase in connectivity has led to businesses' digital transformation, ultimately making room for *as-a-service* business models, in which platforms with business networks and ecosystems are increasingly promoted (Banerjee & Punekar, 2020). This has intensified the development of PSS and its interaction with digital technologies (Rachinger et al., 2019). Digitalization enables servitization as it increases the availability of data during the lifecycle of an offering. Some studies investigated how firms might become more effective, adaptable and practical by ensuring that specific client needs are met while analysing product lifecycle management (PLM) data (Xin & Ojanen, 2017). Others argue the significance of information as a source of value provided by data flows and analysis (Cenamor et al., 2017). Nonetheless, compared to more traditional products and services, there has been little investigation of how to commercialise data and information so as to enable servitization.

2.3.2 Defining digital servitization

Servitization and digitalization are two disruptive processes in today's companies (Tronvoll et al., 2020). Increasing environmental concerns are creating a new competitive framework (Werbach, 2011), particularly in the production and manufacturing sector (Herrmann et al., 2014), in which digitalization and servitization support manufacturing companies as they adress sustainability imperatives (Parida & Wincent, 2019).

These two concepts converge as the combination of new technologies, connectivity and data analysis delivered through services can create new and more sustainable value propositions (Paschou et al., 2020). The integration of these concepts has been proposed in the literature as digital servitization, a field which although still in its growth stage (Gaiardelli et al., 2021), argues the inherent embeddedness of digitalization in servitization building on integrated product-service-software systems (Kohtamäki et al., 2019). Digital servitization can be defined as the provision of digital services which rely on digital components embedded in physical products (Coreynen et al., 2017; Lerch & Gotsch, 2015; Paschou et al., 2020).

According to some authors the fields of digitalization and servitization are partially isolated in research (Paschou et al., 2020). This is due to a lack of communication between research fields and hinders development. The isolation of the terms is counterproductive, as both transitions require firms to cover the gap between the rapidity of digital transformation and the pace of their adaptation processes (Luz Martín-Peña et al., 2018).

When Vandermerwe and Rada (1988) first introduced servitization, they also acknowledged that it poses particular challenges for top management. Since then, despite different definitions and approaches, manufacturers' challenges in service-based business models have become a central theme of discussion in the literature. Some authors have examined the many classification schemes developed to distinguish between different types of product-related services (Lay et al., 2009) and how manufacturing industry players become service providers. This shift requires companies to change their strategies and build new business concepts (Neu & Brown, 2005).

Companies are increasingly interested in digital servitization as they expand their offerings with digital services to achieve increased functionality, better reliability, greater product utilisation and capabilities previously considered beyond product boundaries; all while generating additional revenues and profits, and potentially gaining and sustaining a competitive advantage (Porter & Heppelmann, 2014; Rust & Ming-Hui, 2014). In the past, products were composed mainly of mechanical and electrical parts, but today most manufacturers produce complex systems. This transition brings challenges for top management, challenges that require companies to change their strategies and build new business concepts at several stages, ranging from product design, marketing, manufacturing and after-sale services. It also creates the need for new activities such as product data analytics and security (Negri et al., 2017).

The transformation towards digital servitization requires new capabilities, such as those related to the development and management of digital platforms (Eloranta et al., 2021; Rabetino et al., 2021), and requires a more extensive ecosystem approach (Kohtamäki et al., 2019) As digital servitization drives companies with previously product-centred approaches to undergo a company-wide transformation it revolutionizes their business model, creating new implementation challenges (Favoretto et al., 2022; Paschou et al., 2020).

Digital technologies are not only embedded into products and services but also affect other servitization dimensions, such as a company's culture and processes (Simonsson & Agarwal, 2021). Digital servitization cannot be understood as a rupture or a "newborn" construct by another name (Hirsch & Levin, 1999). It is an expansion of the servitization construct since it is built upon the same conceptual and theoretical foundations as the servitization umbrella (Vendrell-Herrero et al., 2017). It is also being investigated by the same servitization community (Rabetino et al., 2021). Nevertheless, digital servitization adds a new aspect to the complexity of the servitization practices (Favoretto et al., 2022).

2.3.3 Sustainability-as-a-Service

In recent decades, a new paradigm has been identified through different "as-a-service" models. This trend provides a promising scenario in which service-orientated architecture supports the development and deployment of services (Duan et al., 2015). This approach has been extended to multiple value propositions, many of which are IT related (being the most known Software-as-a-Service or SaaS), but expanded to a several other terms, each with their corresponding abbreviations (Ma, 2007). This thesis is not the first occasion in which the conceptualisation of sustainability as a value that can be embedded in a company's offerings is proposed. Ten years ago, Wolfson et al. (2013) explored the intersection between companies formulating and packaging sustainability values for their customers in the shape of a product or a service. They also reflected on the lack of consensus between the propositions in marketing literature and the sustainability objectives of companies.

The last decade has presented companies with changing priorities, due to the appearance of ESG reporting requirements (Arvidsson & Dumay, 2022). Although the concepts of their work have not been significantly expanded, other authors have parallelly explored this concept. In particular, Paiola et al. (2021) shed light on the lack of studies exploring the intersection of these three concepts: digitalization, servitization and sustainability. Confirmed by other schools of thought, in one of the most recent publications to date, Abdelkafi et al. (2023) evaluate systematically different frameworks and methods for sustainable business models including those referring to servitization. Unsurprisingly, among the contributions that have been analysed, some of them include "product-service systems" as a main keyword. The criticisms can be summarised in points which have been already mentioned in previous literature. These include the lack of tools to assess and accomplish the sustainability implications of transitioning

business models, increased data-based evidence from quantitative research methods, the evaluation of risks to avoid whiplash effects and existing field biases (Blüher et al., 2020).

Rabetino et al. (2018) identify a group of scholars who have explored the configurations of sustainable product-service systems as a way for environmental and economic growth. This field includes evolution in the subsequent decade focusing on central topics such as servitization strategies, organisational structures, value chain organisation and other management-related capabilities (Baines et al., 2009). The present work relates to the interdisciplinary community described by the same authors, in which the challenges of adopting servitization strategies are explored and suggestions are generated to overcome such challenges by identifying requirements (Zhang & Banerji, 2017).

This research is positioned at the centre of digitalization, servitization and sustainability, as shown in Figure 3. This integration provides a configuration that can be beneficial for complex and uncertain integrate solutions (Kohtamäki et al., 2019; Kohtamäki, Parida, et al., 2020). In this context, it is expected that servitization will provide valuable support in exploiting the benefits of digitalization. This research presumes that including sustainability in this discussion can support the achievement of industrial sustainability goals, with "service extension" having gained increased importance from policy makers, manufacturing and other industrial sectors (Doni et al., 2019). Furthermore, it can help in avoiding the traps created by digitalization and servitization paradoxes. This is further strengthened by the propositions made by Struyf et al. (2021), who state that digital servitization as a wicked problem (defined as unique and complex challenges that are perceived differently by each stakeholder involved in the transition). Therefore, qualitative, and empirical contributions to this field may be particularly beneficial to the generation and advancement of theory.

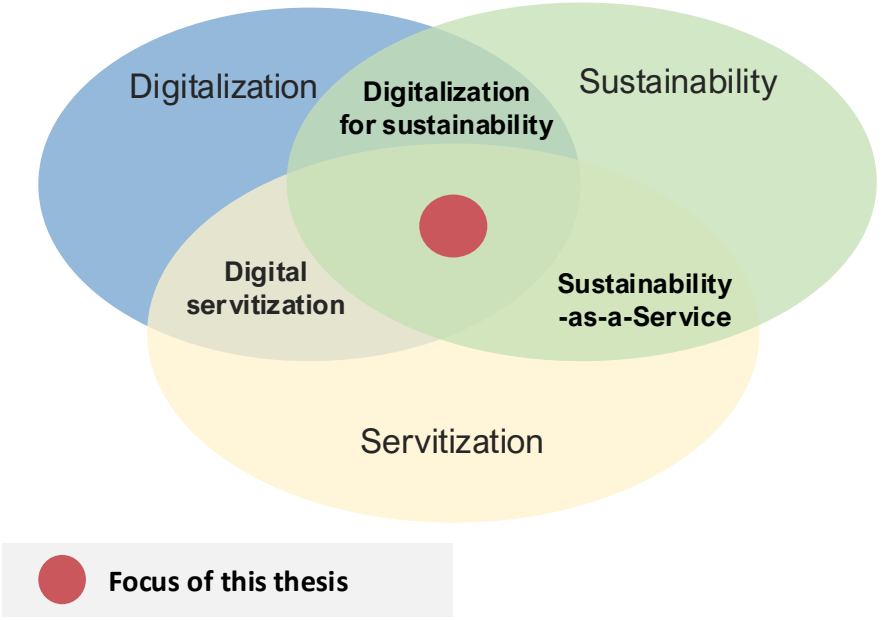

Figure 3. Research framework

3

"Science and everyday life cannot and should not be separated."

– Rosalind Franklin

RESEARCH METHODOLOGY

This chapter presents the authors' research background, the philosophical perspective which guided this work, the research design and the rationale behind planning and execution of the studies and papers. This section also provides insights into how the research questions are answered by the studies and the appended papers.

3.1 RESEARCH BACKGROUND

This research journey began in 2016, with a Master program at Tecnológico de Monterrey, supported by a research scholarship. There, I explored the concept of product-service systems in the context of a circular economy and using lean principles. Looking back seven years, the research problem (relating to the insufficient value of product-centred business models for industrial sustainability) did not seem to have the potential it has today. After graduating, I became a PhD student at the Division of Production Systems at Chalmers, where I was able to explore my long-standing curiosity on product-service systems in the context of digitalization. This was the beginning of five years of multiple research projects in several different industrial sectors. Along the way, my keywords shifted as the field of digital servitization emerged and grew rapidly. This shift better reflected my research interests and more suitably addressed the challenges of the industrial sectors in the projects at hand. Thus, digital servitization, particularly in connection with sustainability, heralded major potential for the research journey ahead.

My personal and professional journey has informed this research work from various industrial perspectives. This baseline has afforded my research work a unique set of different industrial contexts for identifying research problems and answering the established research questions and new theoretical propositions. A summary of this journey followed is given in the subsequent subsections.

3.2 PHILOSOPHICAL PERSPECTIVE

Conducting research is a combination of creative and systematic work, with both sides of the debate on whether it is a science or an art having valid points. Becoming a PhD student, I appreciated both aspects of this historical practice. The way research skills are taught, from one generation to the next through professors, mentors and follow researchers is a practice that brings humanity and personal values into a world that desperately more humanity in its thinking. This is particularly so for research in which we discuss imperative sustainability agendas. As a researcher, I am inspired by the idea of conducting this activity with rigour. This can grant validity to the results across several contexts and provide clarity and explanations for many of the non-addressed world problems, in an era where there is an urgent need for change towards sustainability.

As a curious, analytic thinker, I acknowledge the beliefs and values that I bring into my work. In particular, the term “philosophical worldview” can be used as a tool to describe the researchers’ views regarding the term “reality”. Acknowledging these elements, supports the reader and provides an indication of the rationale behind the selection of research methods and methodologies. These shape the research process and justify the nature of its results.

Researchers are seldom limited to one worldview and draw elements from several schools of thought. I identify mainly with social constructivism as a way of viewing the world. Social constructivists hold the assumption that individuals seek to understand the world in which they live and work, while developing subjective meanings of their experiences which are multiple and varied (Easterby-Smith et al., 2012). This way of viewing the world explains my perspective on business models; concepts which are abstract in nature and depend on the multiple layers of organisations. To achieve a certain aim, this research can benefit from open-ended questioning; this provides the opportunity to hear the social and subjective meanings that are presented through the process of interaction among individuals and within specific contexts. Thus, reality is not perceived as one absolute truth that we can document but, rather, a reality that reality exists in multiple, intangible mental constructions.

Taking advantage of the constructivist worldview, a researcher can explore factors that allow the contextualisation of individuals reality and potentially, create change. The way that we view the world, also allows us to explore how should we investigate it. This set of decisions can be described by the term "epistemology", whereby research is motivated and informed by the researcher's experiences, ideas and interests and is, further conducted according to a suitable design which allows t the reality identified by the researcher to be studied. In this sense, the constructivist approach searches for the meaning created from the interplay between subject and object. Also, there are certain elements of interpretivism, (often combined in research with constructivism), which enable the use of approaches wherein through questioning and observation the researcher can discover and/or generate a rich, deep understanding of the phenomenon being investigated. This explanation justifies the qualitative nature of the methods selected throughout this research journey.

3.3 RESEARCH DESIGN

This research journey was informed by the design research methodology (DRM), which proposes provides an opportunity to systematically plan and develop rigorous research along solid lines of argumentation, while allowing for a variety of research approaches and methods (Blessing & Chakrabarti, 2009). DRM is heuristic rather than algorithmic in nature, meaning that the personal background and interests of the researcher support the uniqueness of the research process. Encouraged by the idea of using a methodology flexibly and thus exploiting the research phenomena available to the researcher, the avenues and specific elements of the research studies were integrated so that they worked towards the research aim and answered the research questions. DRM has specific objectives, as stated by Blessing and Chakrabarti (2009). The ones that deemed most relevant to this research included but were not limited to: allowing a variety of research approaches and methods, conducting rigorous research while developing a sold line of argumentation and supporting the selection of suitable methods to provide a context for the positioning of research projects.

As shown in Figure 4, DRM comprises four stages: Research Clarification, Descriptive Study I, Prescriptive Study and Descriptive Study II (Blessing & Chakrabarti, 2009).

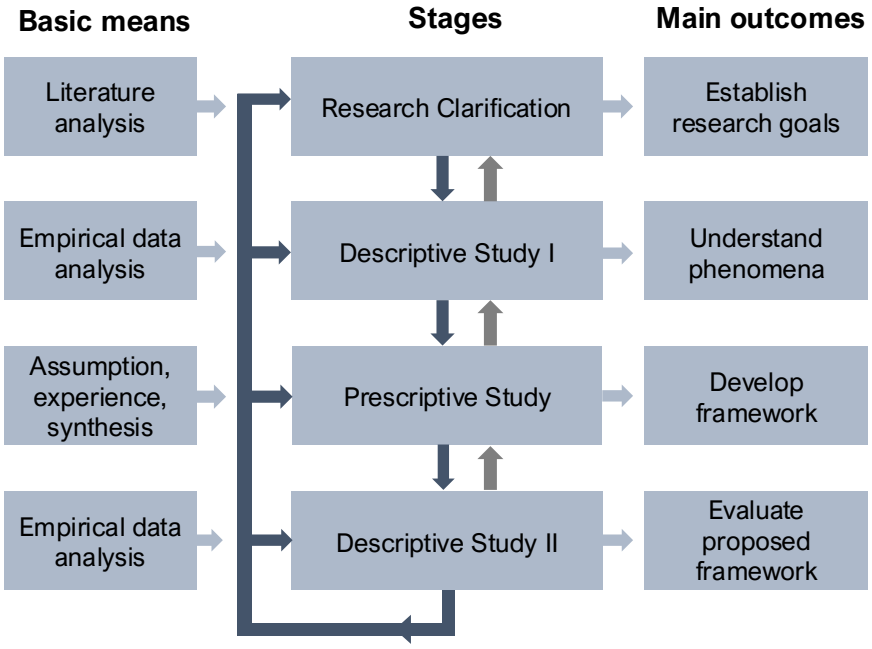

Figure 4. DRM framework (adapted from Blessing and Chakrabarti, 2009)

3.3.1 DRM in the context of this research

One of the characteristics of DRM is the proposed bidirectional iterations through the research stages. This allows for reflection and integration of feedback through the research stages. As indicated in Table 1, the research type 3 (highlighted in red) was considered suitable for the scope and timeframe of this research.

Table 1. Types of design research (Blessing and Chakrabarti, 2009) and selected type for this thesis

Research Clarification	Descriptive Study I	Prescriptive Study	Descriptive Study II
1. Review-based →	Comprehensive		
2. Review-based →	Comprehensive →	Initial	
3. Review-based →	Review-based →	Comprehensive →	Initial
4. Review-based →	Review-based	Review-based Initial/Comprehensive →	Comprehensive
5. Review-based →	Comprehensive	Comprehensive →	Initial
6. Review-based →	Review-based	Comprehensive	Comprehensive
7. Review-based →	Comprehensive	Comprehensive	Comprehensive

The Research Clarification stage is mainly characterised by the researcher's attempts to find evidence to supports her assumptions and thus establish well-defined research goals. The main method of doing so is literature analysis. As shown in Figure 5, the research clarification stage of this work corresponded mainly to Study A, Paper 1; also, this stage is mainly connected to the answering of the first research question. This stage also included the selection of a suitable type of research considering the time frame and situational constraints.

The Descriptive Study I uses a combination of literature reviews and empirical data analysis through as a means of understanding and describing the current situation in practice. As shown in Figure 5, this research stage corresponds to Study B, C and D and its outputs are connected to both the first and second research question.

The Prescriptive Study may be described as a purposeful activity to develops a product which supports design. This research stage is informed by the results and insights generated in the Descriptive Study I and positions relationships between concepts, using the gap in requirements identified in the Sustainability-as-a-Service paradigm. As shown in Figure 5, this research stage corresponds to Study E, and its outputs are mainly connected to the answering of the second research question.

The last study, Descriptive Study II, conducts an evaluation of the design support. Within the framework of this research, the design support corresponds to the output of the previous stage (Prescriptive Study). The decision to conduct this research stage is justified by its relevance in a research context and the best practice of evaluating results throughout the process to determine whether an output can continue to the next stage. This stage is particularly relevant as creative nature of this process and the design of support tools and frameworks requires assumptions. These assumptions are necessary when translating what was found in both theory and practice into the development of an initial idea. However, this stage is considered difficult for many reasons, including time and scope constraints. As shown in Figure 5 this research stage corresponds to Study F; its outputs are mainly connected to the answering of the second research question.

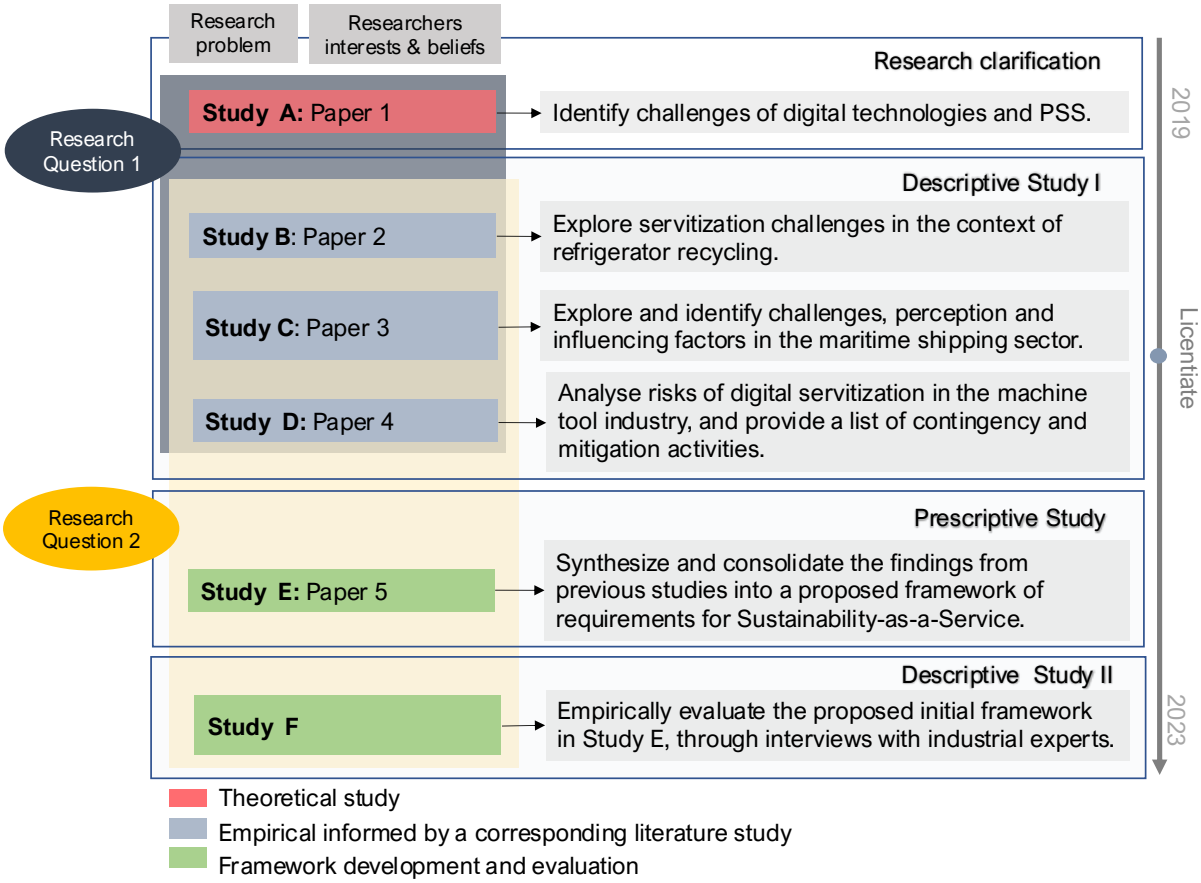

Figure 5. Research design (Blessing & Chakrabarti, 2009)

3.3.2 Qualitative case study design

An exploratory qualitative research approach was beneficial and appropriate as digital servitization is a growing field, with the number of case studies, volume of data and level of industrial awareness still rising. The selection of case studies was also deemed appropriate, given that the researchers constructivist worldview addresses the belief in different realities constructed by the subjects. Thus, the author believes that the transition towards digital servitization is believed to be experienced differently by different companies and the individuals that lead them. The current literature has some documented case studies but the possibility to form a generalisation is still a long way off. To further inform the current body of knowledge, new insights from an industrial perspective could bring benefits and identify context-specific challenges, factors and requirements to guide the development of future theories to guide companies through this complex process.

On this research journey, case study research formed part of the backbone of the qualitative approach. This methodology was deemed relevant as it enables the researcher to study contemporary phenomena in real-life settings, particularly in cases where boundaries between the context and the phenomenon are blurred (Dubois & Gibbert, 2010; Yin, 2018). As previously mentioned, research activities conducted in the descriptive stage were based on a case study approach, informed partially by an interpretivist epistemology, and allowing the focus on experiences of reality. Interpretivists see people as experts of their own experiences, which positions as an aim to understand people social worlds and not change them (Yin, 2018). However, this research approach also references opportunities to maintain a constructivist orientation through the case study.

The studies B, C and D did not have a completely linear sequence across the time horizon of this research journey (as the publication date may indicate). The definition and re-definition of the case boundaries was an iterative process. In their work, Ragin and Becker (1994) discuss how moving back and forth between theoretical ideas and historical evidence is one of the most suitable strategies for a theoretical context that frames a case. Furthermore, the definition of the cases, in which posing such questions such as, "what are the cases instances of?". These questions acted as support for the framing of the studied system and sparked long reflective sessions. This may be taken as a positive sign as it has benefitted the iterative nature of the research process. Moreover, the dual process of finding both internal and external validity in the case definition has often blurred the case boundaries (Dubois & Gibbert, 2010), which may be an indication of the relevance and timeliness of the research topic selected (Ragin & Becker, 1994).

In their article, Dubois and Gibbert (2010) build on the argument of Eisenhardt and Graebner (2007) who suggested that the output of research work that builds theory from cases is highly valuable. The article emphasises the interesting nature of the results from case studies and the high impact they have among other research outputs (Bartunek et al., 2006; Eisenhardt, 1989). Therefore, this approach of this thesis was intended to generate and test theory by exploring complex relationships between case study, empirical phenomena and theory.

3.4 RESEARCH METHODS

Section 3.3 described the logic and reasoning behind the design of the studies in this research journey. In this subsection, Table 2 describes the methods followed, along with the data collection and analysis strategies in study A-F. This subsection is structured according to the research design presented in Figure 5. A summary is presented in Table 2, but additional details about the methods can be found in the appended papers.

Table 2. Research methods and data collection for the appended papers

Stage	Study	Paper	Methods	Data collection and analysis
Research Clarification	A	1	Literature review	Systematic literature review with deductive coding.
Descriptive Study I	B	2	Single case study	Five visits to a refrigerator recycling plant in Sweden and one visit to a recycling plant in Italy, literature review, observations and workshops
	C	3	Multiple case study	Literature review, company visits, semi-structured interviews, coding by multiple researchers.
	D	4	Multiple case studies	Literature review, development of digital services, questionnaire and risk analysis
Prescriptive Study	E	5	Framework development	Literature review and synthesis of Studies B, C and D to build a theoretical framework
Descriptive Study II	F		Framework evaluation	Interviews with industrial experts to evaluate the framework which resulted from Study E

3.4.1 Research clarification

Study A (Paper 1) conducted a systematic literature review that aimed to identify the interactions between digital technologies and product-service systems, by performing a thematical analysis to identify enablers and challenges.

3.4.2 Descriptive study I

The Descriptive Study I was composed of case studies which are summarised in Figure 6 and more details about the methods can be found in the papers.

Study B (Paper 2) performed a case study, which groups an organization as a case and defines it within the refrigerator recycling facilities of a larger recycling organization. The collected data included multiple observations of the recycling facility, interviews, and workshops with the operators to understand their working processes.

In Study C (Paper 3), multiple case studies were conducted with 13 companies (Creswell & Creswell, 2017; Miles & Huberman, 1994). This study conducted an integration of the PESTEL (political, economic, social, technological, environmental, and legal) and DPSIR (Driver-Pressure-State- Response) frameworks. PESTEL is a tool that focuses on the analysis of external factors that impact an organization (Johnson et al., 2008); while DPSIR is a stress-response model used to concretize problems into solutions (EEA, 1995; OECD, 1993; Zhang & Xue, 2013). The integration of these frameworks provided potential to capture the multidimensional nature of the system investigated (Tsangas et al., 2019). More details about the selection of the case studies and their data collection protocols are provided in Paper 3.

In Study D, a multiple-case study (Yin, 2018) used risk analysis to explore receptiveness towards three digital services by three industrial companies. The data collection protocols, analysis and results are documented in Paper 4.

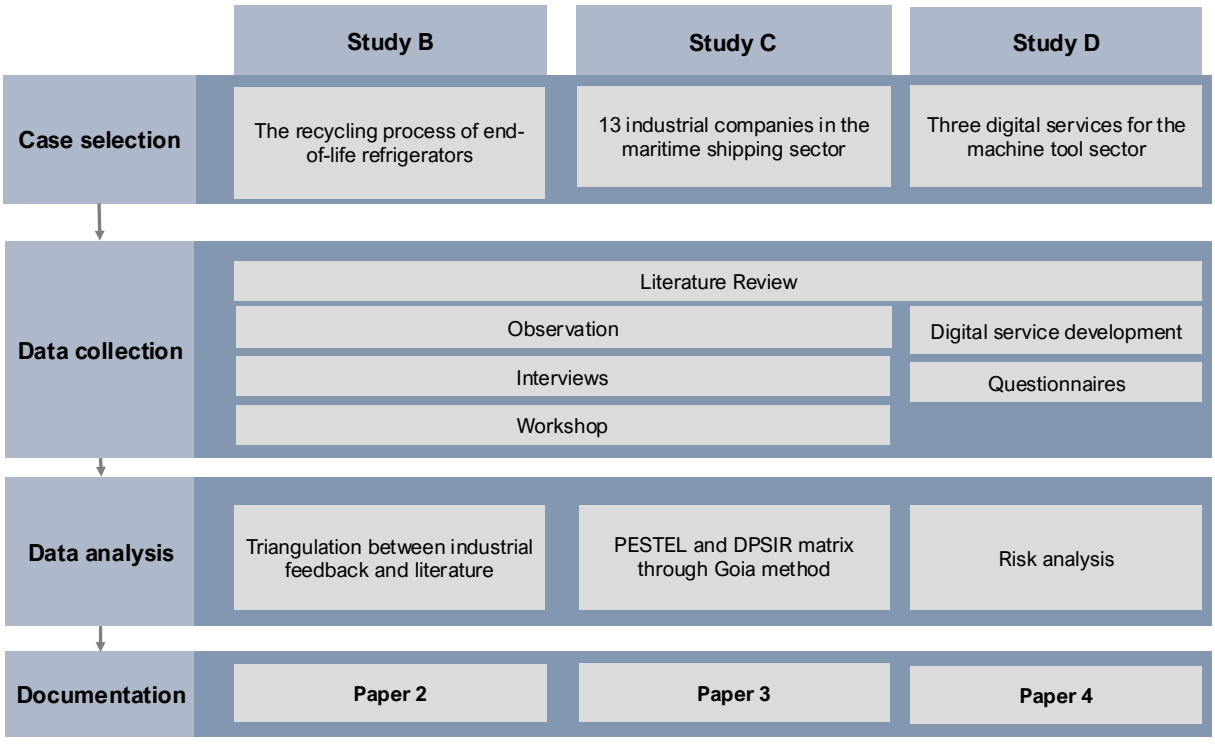

Figure 6. The case studies that were conducted

3.4.3 Prescriptive study I

Study E (Paper 5) was informed by the outputs of the Descriptive Study I. Moreover, Study E conducted a literature review and then synthetised the empirical findings of the case studies (Studies B, C and D). This synthesis was empirical input to the development of a theoretical framework (Cornelissen, 2017; Jaakkola, 2020).

3.4.4 Descriptive study II

Study F then empirically evaluated the theoretical framework proposed in Study E by conducting five interviews with industrial experts (see Table 3). The criteria for selecting the interviewees included working first-hand in the development of digital services or supporting servitization transitions. The selected interviewees were also selected based on their explicit expressions of interest in the field of digital servitization and sustainability. The interviews followed a semi-structured approach which allowed to adjust the interview strategy to maximize the value captured from the interviewee's expertise. These interviews were conducted online, lasted approximately 60 min (but with some extensions requested by the interviewees) and were recorded and then transcribed. The analysis included a deductive coding (Creswell & Poth, 2017) based on the framework presented in Study E (Paper 5).

Table 3. Interviewees selected for Study F

Interviewee	Role	Company description
1	Partner and Technical Specialist	Technology integrator which provides infrastructure, software and consulting services that support digital transformations.
2	Sustainability Technology Architect	Integrator of plant level and enterprise networks that connect people processes and technologies to simplify customers' experience and drive productivity.
3	Project Manager in Digital Transformation	
4	Industrial Digitalization Executive	Solution provider for manager applications, infrastructures and IT services; helps customers make use of data, analytics and AI to create value.
5	Impact Executive	Global professional service provider which supports clients in modernising technology and processes by focusing on IoT, AI, software engineering and the cloud.

The interview protocol was designed to: (1) understand the context of the interviewee's employer; (2) capture their experience working with digital services or digital servitization; (3) identify their perspective on sustainability in their services; and (4) evaluate each section of the framework proposed, based on the research quality criteria by (Tracy, 2010).

Interviewees 1, 2 and 3 gave a first-hand perspective, focusing on narrating their own service design and delivery process. The interview protocol was adapted to capture most of their rationale behind the embedding of sustainability in the digital services developed in their companies. Moreover, Interviewees 4 and 5 provided a perspective on service provision and consulting, whereby the transition to digital services was perceived as a process without necessarily having a particular service in mind.

4

"*It matters little who first arrives at an idea, rather what is significant is how far that idea can go.*"

– Sophie Germain

RESULTS

This chapter presents the outcomes of the conducted studies. Figure 7 presents the relationships between the studies conducted, their documentation as papers and the subsection where they are summarized. In this figure, the darker circles represent a major contribution to the answering of a research question, whereas a lighter circle represents a minor contribution. Further subsections 4.1 to 4.5 summarize the main outcomes of each paper is included with particular focus on the elements which contribute to the answering of the two research questions. Section 4.6 presents the results from Study F. At last, Section 4.7 presents a summary of the answers to the research questions.

	Study A **Paper 1** Section 4.1	**Study B** **Paper 2** Section 4.2	**Study C** **Paper 3** Section 4.3	**Study D** **Paper 4** Section 4.4	**Study E** **Paper 5** Section 4.5	**Section F** Section 4.6
Aim of the study	Identify the challenges and enablers of PSS and digital technologies	Evaluate the feasibility of digital servitization in refrigerator recycling	Identify the influencing factors for the adoption of digital servitization	Identify the risks associated with the adoption of digital servitization	Identify the requirements for digital servitization	Empirically evaluate the proposed framework
RQ1) What are the **challenges** of digital servitization for sustainability?	●	●	●	●	○	
RQ2) What are the **requirements** for Sustainability-as-a-Service?		○	○	○	●	●

Figure 7. Relationship between the research questions and the studies

4.1 PAPER 1

State-of-the-art on Product-Service Systems and Digital Technologies. **Clarissa A. González Chávez**, Mélanie Despeisse, and Björn Johansson (2021) Presented at the International Symposium on Environmentally Conscious Design and Inverse Manufacturing (EcoDesign 2019), Yokohama, Japan, 25-27 November 2019. Published in EcoDesign and Sustainability I. Sustainable Production, Life Cycle Engineering and Management, Springer Singapore, pp. 71-88.

Recent decades have seen the potential for exploiting human and industrial capabilities in manufacturing. Megatrends such as digitalization, automation and connectivity are changing the way organisations and their customers perceive value. Manufacturing companies have invested in the development of personalised products with value-added services, known as PSS. The intersection of the digital and material world could provide the necessary infrastructure to implement feedback-rich systems throughout the product's lifetime. This will facilitate information transparency and process circularity, generating additional possibilities to achieve more sustainable processes. The convergence of these research trends has contributed to a strong PSS development, which is supported by over twenty years of research.

This paper aimed to understand the interactions of digital technologies and PSS by identifying enablers, challenges and effects. It also aims to contribute to the ongoing discussion regarding the relationship between PSS and sustainability. The article identified seven enablers which are: customer relationships, new service provision, new distribution channels, big data, increased visibility of lifecycle, business analytics and a reduced need for external assistance.

This paper also identified six challenges which are: (1) customer perception, (2) the value of data, (3) technical capabilities, (4) policies and regulations, (5) economic feasibility and (6) data privacy. The first challenges, customer perception, was identified due to the found *service-for-free* attitudes documented in the literature; a situation that can create complexities around pricing strategies. The second challenge, value of data, does not solely refer to data collection, but also to the correct visualisation and usage of the information embedded and its use for decision-making. The third challenge, technical capabilities, referred to the need for suitable synergies between customers and companies to enable co-designing processes. This challenge includes both capabilities from perspectives of infrastructure and available skills. The fourth challenge highlights the need for the institutionalisation of the sharing economy and the need for support in data-sharing policies. The fifth challenge, economic feasibility, highlights the financial exposure and risks faced by PSS suppliers when the advancement of capital costs is required. Last, the sixth challenge summarizes the need for safe data exchange and the monetization of product data as challenging activities for PSS suppliers.

This study characterised the connections between PSS and digital technologies, as well as it positions future research that can help deploy more successful and sustainable PSS. To understand the existing scenario, the research revealed a list of enablers and constraints. From their analysis, the authors concluded that the development and operation of efficient PSS that comply with sustainability concerns is strongly dependent on the suitable, in-depth consideration of other organisations and stakeholders engaged in the process.

4.2 PAPER 2

Achieving Circular and Efficient Production Systems: Emerging Challenges from Industrial Cases. Mélanie Despeisse, Arpita Chari, **Clarissa A. González Chávez**, Xiaoxia Chen, Björn Johansson, Víctor Igelmo Garcia, Anna Syberfeldt, Tarek Abdulfatah & Alexey Polukeev (2021) Presented at International Conference on Advances in Production Management Systems (APMS 2021), Nantes, France, 5–9 September 2021.

Circular economy (CE) is an umbrella concept promoting the retention of the economic and environmental value of materials. It aims to extend the useful life of products or recapture materials in loops and give them a new life. CE strategies include industrial waste management strategies and regenerative approaches, such as biomimicry. These offer opportunities to decouple the environmental impact of products from the value delivered to customers and captured by businesses. This paper presents the empirical findings of three case studies exploring novel circular solutions as part of a collaborative project between industry and academia: Enabling REuse, REmanufacturing and REcycling Within INDustrial systems (REWIND). The first pilot addresses the case of refrigerator recycling and corresponds to Study 2. Therefore, Section 2.1 in this paper is the most relevant part when it concerns describing the case addressed in this research.

The first industrial pilot focused on recycling Waste from Electrical and Electronic Equipment (WEEE). Stena Recycling currently handles a wide range of WEEE products. In Sweden, it is the responsibility of end users to transport end-of-life refrigerators to collection centres. However, the current collection system does not promote value-retention, as the refrigerators are stored outdoors. Better integration across the supply chain and further development of collection centres are needed to retain the value of end-of-life refrigerators.

Stena Nordic Recycling Center is currently exploring the potential of physical and cognitive automation (such as robotics, machine vision and learning) to aid recovery processes like cleaning, separation, evaluation and shredding. Advanced technologies could help operators in more complex or dangerous processes, such as collecting compressors. Physical automation could prevent injuries and accidents while increasing the efficiency and value recovered during the dismantling process.

Stena's intention to transition to more CE has led to discussions about remanufacturing and refurbishing refrigerators as alternatives to recycling. To implement these alternatives, operators must be upskilled and digital training tools such as AR/VR can be used.

The potential of capturing data from end-of-life products as a source of value is appealing to manufacturers. However, commercializing data from products and enabling collaboration along the value chain presents several challenges for Stena. For example, the placement of the compressor and information labels are not standardized between different brands and models of refrigerators, hindering data capture and process automation. The data required to teach AI to recognize the product and assist in automating the compressor removal would require a database of at least 100,000 images, with the benefits still unclear.

Stena strives to innovate and achieve more sustainable recycling processes. However, collaboration with manufacturers, collection centres and other logistics actors is difficult due a lack of incentives. CE is gaining attention, but the supporting information flows are not yet in place. Manufacturers such as Electrolux focus on new product designs using recycled materials, but there are new efforts to tackle end-of-life problems. This delay between design improvements and their benefits presents a major barrier to collaboration between manufacturers, collection centres, recyclers and other actors in circular value chains when it comes to tackling today's WEEE at scale.

4.3 PAPER 3

Advancing sustainability through digital servitization: An exploratory study in the maritime shipping industry. **Clarissa A. González Chavez**, Selma Brynolf, Mélanie Despeisse, Björn Johansson, Anna Öhrwall Rönnback, Jonathan Rösler and Johan Stahre (forthcoming). Submitted to Journal of Cleaner Production on 24th of April 2023 (under revision).

The maritime sector is a major pillar in global logistics, transportation and commerce and is facing growing pressures to become more sustainable. Digital servitization is becoming increasingly important for maritime business actors, as it can support dematerialization, extend lifecycles, generate additional revenues, retain customers and engage with new ones in tighter relationships. This study explored the influencing factors for the adoption of digital servitization in maritime shipping. It used a case study approach to explore internal and external factors that influence companies in the maritime shipping sector in Northern Europe.

The case studies conducted for this study included interviews, whose transcripts were analysed by using a combination of PESTEL (political, economic, social, technological, environmental and legal) and DPSIR (Driver-Pressure-State-Impact-Response). PESTEL is an analysis tool focused on external factors impacting an organisation, while DPSIR is a stress-response model used to guide reporting and assist policymakers to identify cause-effect relationships between humans and the environment. The results are presented into three aggregate dimensions based on the PESTLE framework: (1) political and legal (2) economic and technical and (3) environmental and social. The results are discussed using the DPSIR framework.

This study investigated the state of the art of service-based business and digitalization models and their implications for sustainability within the maritime shipping industry. The results show that the elements of digitalization that provide the highest value are in constant evolution, with the role of connectivity and data capture, analysis and usage remaining critical topics. The challenges and opportunities identified will impact workforce requirements, highlighting the need for skilled employees to support the adoption and exploitation of digital technologies, data acquisition, usage and implementation. Digital servitization can support the sustainability transition through shared costs and responsibilities to redistribute fairly the benefits across the value chain. However, unclear responsibilities and roles can hinder the prioritisation of sustainability-oriented changes.

This study provided a snapshot of the status of service-based business models in shipping. Thew shipping industry is expected to remain a key factor for the global economy in the foreseeable future, which highlights the need for future development of digital servitization in this sector. The authors suggested the need to explore how companies can benefit from digital servitization to reduce the environmental load of operations.

4.4 PAPER 4

Analyzing the risks of digital servitization in the machine tool industry. **Clarissa A. González Chávez**, Gorka Unamuno, Mélanie Despeisse, Björn Johansson, David Romero, Johan Stahre (2023). Published in Robots and Computer-Integrated Manufacturing Volume 82, art. no. 102520. https://doi.org/10.1016/j.rcim.2022.102520

Machine tools are key assets in production and their performance directly impacts product quality and production efficiency. According to CECIMO (a European association of manufacturing technologies), an average of 80% of machine tools are still in service ten years after their installation and 65% are still in service after 20 years. In this manufacturing context, digital servitization has acquired increased relevance as the evidence of product-centred business models is insufficient to indicate success.

This study identifies a lack of understanding of how the risks of specific digital services are perceived and a failure to inform the machine tool industry about the potential negative implications. Based on the identified research gap, this study poses the following research question: *What are the risks associated with the adoption of digital servitization in the machine tool industry?* To address this research question, we developed three digital services and assessed the potential risks associated with their implementation, as well as identified mitigation and contingency activities.

The machine tool industry is a major supplier of components for many products made by various actors in the manufacturing industry. The highest-rated risk among those that were considered unacceptable was identified in the legal category, with the concern being that partners would fail to discuss all relevant terms of the digital service. The risks in six out of nine categories presented in the results (business, project, strategy, legal, team and technical) included integrating digital services with ERPs and MES, unavailability of connected machines and a potential lack of data. Moreover, having multiple industrial sectors in one value chain could pose a risk, as there is no understanding yet of whether digital services can be adapted to individual actors. The results of this study show the need for future research to explore the economic feasibility of adopting new business cases with risk-sharing strategies in place.

Companies expressed concerns about the implementation of the services incurring more costs than the regular manufacturing process, and data ownership agreements need to be discussed to avoid problems induced by sharing industrial partners' data. Additionally, the lack of available talent caused by the reshuffling of the workforce because of the recent global pandemic has created concerns about the lack of availability of highly trained personnel to carry out technical installations. The technical risk category (F) included four of the risks considered high, such as the multicamera location required in the digital services being too complex to use in a real warehouse, facing installation problems, and unplanned license and maintenance costs.

The most important mitigation and contingency activities included: assessing connectivity and stability with open data sets; establishing communication and collaboration with ERP and MES software providers; calculating and showing cost estimations across complete lifecycles; implementing NDAs and data-ownership agreements; and conducting frequent follow-ups.

This research discusses the importance of creating joint-ownership agreements between partners to address the unacceptable risk of lack of understanding of the digital service terms. To address the risks that are considered high, strategies such as evaluating data formats, developing audits of documentation and establishing closer relationships with ERP and MES software providers are suggested. It is also important to evaluate the simplicity of the implementation and start with small wins, avoiding disruptions to the most critical systems.

4.5 PAPER 5

Sustainability-as-a-Service: Requirements Based on Lessons Learned from Empirical Studies. **Clarissa A. González Chávez**, Mélanie Despeisse, Björn Johansson, David Romero and Johan Stahre (forthcoming). Submitted to the International Conference on Advances in Production Management Systems (APMS 2023), Trondheim, Norway, 17-21 September 2023 (minor revisions ongoing to address reviewers' comments).

The journey towards digitalization and sustainability of manufacturers requires an understanding of their status and desired state. New business models, like digital servitization, can support the transition from pilots to full shop-floor implementations and the innovation of the end-to-end value chains.

There has been plenty of research into the servitization phenomenon analysing individual cases and proposing sector-specific frameworks. However, there is still room for general frameworks that capture best practices and common mistakes in the manufacturing sector as companies embark on their (digital) servitization journey. This study aims to provide an overview of the main lessons, including challenges, opportunities and success factors, experienced in research projects when companies look at different degrees of digital servitization in their business models and value offerings. These make their lessons learned transferable to scholars and other industrial companies that are considering starting their digital servitization journey. Therefore, the research question addressed in this study is: *What are the key requirements for companies who want to successfully begin or continue their servitization journey towards digital servitization?* This study draws its strength from using exemplification as a valuable way of illustrating findings, thus making it more relatable for researchers and relevant industrial companies.

This study conceptualises Sustainability-as-a-Service as the creation and delivery of digital services, which are the output of a digital servitization business model and strategy. It is proposed as a service that extends the relationships between sustainability and service beyond the incorporation of sustainability into services, directing the focus onto sustainability itself. To develop sustainable offerings, companies and value chains must consider the digital service qualities defined by Romero et al. (viz. inseparability, intangibility, inventory (perishability), inconsistency (variability), and involvement), plus a broader scale of multi-dimensional value co-creation based on the TBL. The concept of Sustainability-as-a-Service includes a vision of smart, continuous, dynamic and evolutionary value adapted to a certain place, time and group of people.

The authors propose an initial framework which translates into requirements that must be considered. The categories of the proposed framework are divided into: (i) overarching elements which include external factors, technology enablers and organisational skills, (ii) value chain considerations which include the antecedents and the scope of the intended transformation; and (iii) company considerations. Within these categories, the actions: "define", "identify", "ensure", "integrate", "evaluate", "develop", "apply" and "build" were repeatedly found in the cases. These can be used to guide the activities required by companies to position themselves in a strong value chain and ensure a successful digital servitization process.

This study has theoretical and managerial implications. From a theoretical perspective, the study identifies the state-of-the-art in terms of frameworks and methods for "digital servitization" and synthesizes them in the initially proposed framework. From a managerial perspective, the findings can support companies by making the results more relatable and the list of requirements can better orientate their efforts towards digital servitization.

4.6 STUDY F

This section presents the empirical evaluation of the framework of Requirements for Sustainability-as-a-Service presented in Paper 5. This framework comprises four dimensions and eight elements as shown in Figure 8.

As described in 3.4.4, this study entailed five semi-structured interviews with industrial experts in the areas of digitalization, servitization and sustainability. In the proposed framework, the author has stated in Paper 5 that: *"The transformation stages are not expected to be a one-size-fits all, but this list can serve as a starting point to mitigate the risks in facing challenges along the way" (González Chávez et al. 2023)*. Therefore, the proposed framework is subjected to an evaluation stage, to evaluate its applicability in other industrial scenarios.

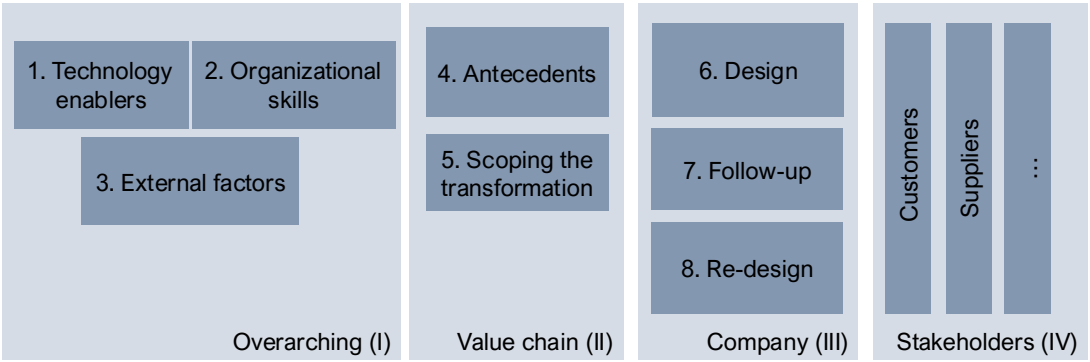

Figure 8. Framework of requirements for Sustainability-as-a-Service (from Paper 5)

For improved visualisations, Figure 8 presents the framework from Paper 5 with an additional numerical coding for each box. However, it should be noted that this enumeration does not indicate a suggested sequence for the framework. In this subsection, the main blocks are named "dimensions" (Roman numerals) and the internal squares (Arabic numerals) are named "elements". To cover most of the framework, this section presents only some of the most relevant evidence from the interviews conducted.

One of the highlighted aspects of the proposed framework is the need for companies to work simultaneously an internal level **(Dimension III)** and with the complete value chain **(Dimension II)**:

> *"We need to understand what is happening upstream and downstream. This is why we need to work with multiple companies to create a valid chain of data […] because there are multiple regulations in production spaces" – Interviewee 2*

At Dimension I (Overarching considerations), the interviewees highlighted the relevance of exploring technology enablers and organisational skills simultaneously:

> *"They do have amazing capabilities but they're failing and packaging them as part of a real offering." – Interviewee 4*

> *"The limitation isn't usually the technology, but the organisational boundaries." – Interviewee 1*

At **(Dimension I)** Overarching considerations, the interviewees discussed **(Element 1)**. In this regard, the role of data was repeated in several instances, specifically in connection with how it enables the definition of suitable costing methods:

"We charge on the basis of complexity and scale of the data, so we need to know how many data points there are" – Interviewee 1

Also, in this section, the role of AI, machine learning and deep reinforcement was highlighted as an enabler of new business models:

"AI and machine learning are becoming the norm, so we have gone beyond the principles of digitalization"- Interviewee 5

(Dimension I) Overarching considerations, **(Element 2)** Organizational skills found some of the richest discussions in connection to the role of trust in the use of data:

"There needs to be trust of who is using the data and whether the data has been pre-approved to be used by others" – Interviewee 2

Also, the need for upskilling for both technical requirements and new business model needs, was addressed:

"In recent years, companies have been investing heavily into upskilling their people and hiring more data scientist and engineers. But they are struggling to capture the capabilities of highly experienced employees." – Interviewee 4

(Dimension I) Overarching considerations, **(Element 3)** External factors led to relevant discussions regarding how current legal and financing strategies hinder digital servitization:

"In terms of economic regulations, the depreciation of products in balance sheets is a complex topic that can hinder servitization. Many actors (…) know that different contracts can represent financial risks." – Interviewee 4

This section also captures insights into the general perception of sustainability by industrial companies, with a rather positive outlook for the near future.

"Sustainability is widely misunderstood […], it has become a marketing tool mainly connected to CO_2 emissions and carbon credits" – Interviewee 4

"Five years ago, it was a challenge to attract attention towards sustainability and today competition in these topics has increased radically" – Interviewee 5

Then, at **(Dimension II)** Value Chain many of the elements of **(Element 4)** Antecedents were discussed thoroughly. Some of the most remarkable interview insights included:

"The selling of services has already been observed as a successful strategy from a systems' engineering perspective, and that can be translated into services" – Interviewee 1

The interviewees also highlighted the importance of using assessment tools to avoid the servitization paradox in collaboration with other stakeholders.

"We identified that there are three or maybe four main levels of maturity (by using their own tool) where the percentage of the portfolio focusing on traditional services was noticeable and they didn't see the revenues coming from amazing business model innovations." – Interviewee 4

Then, at **(Dimension II)** Value Chain, **(Element 5)** Scoping the transformation, the interviewees highlighted how they need to ensure engagement, to evaluate the openness of the stakeholders towards implementing digital services:

"We need to approach the sales of our software with change management and governance of the whole system and walk the stakeholders with leadership, engineer and management areas to mould in a new way of operating" –Interviewee 2

Furthermore, at **(Dimension III)** Company level, **(Element 6)** Design, a point where the companies are suggested to define target indicators. Although this framework does not explicitly and strongly advocate for the definition of the economic feasibility of the business model transition, it is relevant to consider it as part of the economic pillar of the TBL of sustainability approach suggested. This point was highlighted in the following statement by Interviewee 4:

> *"I always say to my customers (...) you have to be very impatient with profitability (...), whatever you're offering to your customers make sure that you're able to make money out of it." – Interviewee 4*

Then, at **(Dimension III)** Company level, **(Element 7)** Follow-up, there were valuable discussions in connection with the quality and ownership of data:

> *"Creating meaningful insights from data in a sustainability environment requires high degree of data maturity and quality" – Interviewee 5*

> *"Our company doesn't own the data. We can never use it, even if we know there is a lot of value for other of our clients." – Interviewee 1*

And at **(Dimension III)** Company level, **(Element 8)** Re-design, there were some reflections on the shift in business models, including:

> *"Risk mitigation: there is a need to understand that risk-based contracts force you to calculate and excel at advanced service provision by thoroughly understanding the data and behaviour performance of machines and customers" – Interviewee 4*

Finally, it is relevant to point out that one of the main contributions of this framework is the positioning of sustainability at the core, which is highlighted by the interviewee. In one of the interviews, their journey was described as:

> *"[before] a lot of the reporting around sustainability was voluntary. Companies were gathering sustainability data to find out where they were and how to get better. Now (...) the focus has shifted to mandatory reporting." – Interviewee 1*

Their perception of how companies are approaching sustainability highlighted how the conflicting nature of what has been documented in the literature has led to a sustainability paradox:

> *"There's a huge positive growing trend around the topic of sustainability but my opinion from what I see with industrial companies is that it's vastly misunderstood – to the point where sometimes they've even seen this topic of sustainability being somewhat abused as a marketing thing." – Interviewee 4*

> *"This whole push now from the European Union is just one part the of whole CSR (Corporate Social Responsibility) frameworks coming out. It's a lash back on green washing that started with funds. 'This is a green fund you should invest here' and then it turns out that they weren't as green as people thought!" – Interviewee 1*

In some instances, the framework and a brief screening of Paper E was shown in the interviews. The interviewees reacted positively to the equal weight given to organizational skills and technology enablers and expressions such views as:

> *"This is fascinating! It occurs to me that it resembles a maturity assessment that I developed for future roadmaps within portfolios and moving from foundational services to advanced ones. I found it to be an amazing tool for creating awareness, getting people planning, talking and changing their mindset, with the main result of them creating their first ever servitization roadmap." – Interviewee 4*

As for future steps, the interviews made statements about the shift from strategy to materializing plans, for instance:

> *"You can have the most perfect servitization strategy, but companies need to go back and analyse their current portfolios and see that they are already on a journey" – Interviewee 4*

> *"From a strategic perspective, from the moment a manager is in charge of a facility they need to be aware ahead of time of what possibilities they have to be more sustainable, so engineers are empowered to make decisions" – Interviewee 3*

The qualitative analysis of these interviews included a step, in which the researcher identified those elements of the proposed framework which were not discussed at all during any of the interviews. The resulting list include very few elements, such as: identifying module pre-dependencies, strategies for end-of-life data collection, end-of-life data flows and some rather specific technology enablers such as traceability tools and automation for data collection. The list, which is considered rather short in proportion to the coverage of the rest of the framework, can be an indicator of the overall relevance of the proposed topics with the experts interviewed. A more extensive reflection on this matter is included in the Chapter 5.

4.7 RELATIONSHIP BETWEEN RESEARCH QUESTIONS, PAPERS AND CONTRIBUTIONS

This subsection summarises the answers to the research questions. The main contributions of each appended paper are presented in four thematic categories in Table 4 (RQ1) and Table 5 (RQ2).

Table 4. Map of papers and contributions to research question 1

RQ 1) What are the challenges of digital servitization for sustainability?		
Categories	**Appended paper**	**Contribution**
Economic and technical challenges in digital servitization	Paper 1	Lack of definition of value of data, missing technical capabilities, unclear economic feasibility.
	Paper 2	Lack of economies of scale, visibility across lifecycles. Also, undefined value of data, concerns about data privacy, lack of visualisation tools and technical capabilities, non-standardization in managed products leading to high product variability. Lack of visibility and capabilities to forecast demand.
	Paper 3	Lack of knowledge the use of digital tools, availability of data, connectivity. Lack of digital infrastructures, while experiencing technology push from suppliers. Difficulty to define the value of data, develop suitable costing methods and define value. Aversion to risks connected to investments for equipment upgrading.
	Paper 4	Lack of understanding around digital tools, data availability, connectivity and definition of suitable costing methods and value definitions.

Organizational challenges in digital servitization	Paper 1	Identifies challenges in customer perception towards PSS and uncertainty on economic feasibility.
	Paper 2	Lack of collaboration and visibility across value chains. Lack of incentives and data structures that facilitate data-sharing.
	Paper 3	Small companies in complex value chains experience resource shortage, siloed conservative companies, lack of loyalty perceived from workforce, push from a digitalized supply chain with varied levels of digitalization across companies. Lack of understanding of customers neds. Poor understanding of upskilling strategies.
	Paper 4	Identifies risks in the adoption of servitization across supply chains and risks connected to information flows across stakeholders
Contextual factors which hinder digital servitization	Paper 1	Identifies challenges in terms of policies and regulations
	Paper 2	Perceived challenges in connection to regulation compliance. Complexity to define functional business models based on the process requirements for end-of-life processes.
	Paper 3	Impressionable markets, high competitiveness and complex differentiation, decentralisation trend. Lack of incentives and regulations.
	Paper 4	Agreements, connectivity, cybersecurity, data agreements lack of open-source software for data development, standards
Available support for digital servitization	Paper 3	Lack of support tools and frameworks for the adoption of servitization and the identification of value opportunities.
	Paper 5	Lack of available tools and methods that embed sustainability

Table 5. Map of papers and contributions to research question 2

RQ 2) What are the requirements for Sustainability-as-a-Service?		
Categories	**Appended paper**	**Contribution**
Technical and economic requirements	Paper 2	New revenue streams, commercialise flexibility, visualisation, procurement integration and value of data
	Paper 3	Need for sensors, visualisation, control systems, automation and transparent and timely data sharing. Need for trials to evaluate economic trade-offs.

	Paper 4	Timely and transparent data sharing, simulation, embed interoperability, model validation and security.
	Paper 5	Manufacturing configurations, stakeholders, involvement in investment and implementation and defining pre-required infrastructures
Organisational requirements	Paper 2	Address data silos, for loyalty and integration across stakeholders
	Paper 3	Openness for data sharing and for system integration. Need to engage in change management to address resistance to change. Required upskilling and strategies for workforce retention.
	Paper 4	Capture knowledge, document audits, interoperability matches and standards before implementing new services, skills and mutually beneficial contracts
	Paper 5	Need for trust towards institutions and product-services, which can be built through competence development, openness, reliability, communication, empath and support, transparent and timely data sharing
Contextual requirements	Paper 2	Regulations, compliance, digitalization level of stakeholders. Openness to data-sharing across value chains and identification of environmental requirements and creation of value propositions that allow compliance
	Paper 3	Need to follow market trends and collaborate with authorities in the development of incentives. Industrial transition towards openness and maturity (organizational and technological). Increased need for strategies to comply with regulations from reporting perspective.
	Paper 4	Digital security concerns and defining data ownership.
	Paper 5	Overall shift towards increased regulations and shifting power relationships.
Support for transition towards sustainability-as-a-Service	Paper 5	Synthesis of requirements for Sustainability-as-a-Service
	Study F	Evaluates the findings from previous studies and generates insights about future steps.

4.7.1 RQ1: What are the challenges of digital servitization for sustainability?

Changing the business model of a company is a transition that can take enormous time and effort (Björkdahl & Holmén, 2013). It is normal for changes with so much complexity to face various kinds of challenges. This research question aims to understand and categorise the many challenges that can be (and are) faced when attempting to adopt digital servitization which its core value of sustainability.

Paper 1 provided the challenges associated with the use of digital technologies and product-service systems. Paper 2, as part of Study B, identified the technical and design challenges which hinder sustainability and circular business models in the context of refrigerator recycling. Paper 3 explored and identified the challenges associated with digital servitization and sustainability in the maritime shipping sector. Paper 4 performed a risk analysis on the adoption of three digital services in the machine tool industry. Paper 5 includes and transforms the challenges from the previously mentioned studies. Moreover, Paper 5 identifies the lack of available support methods which embed sustainability while supporting companies to explore digital servitization.

As presented in Table 4, the challenges identified through the papers are categorised in: (1) economic and technical challenges in digital servitization; (2) organisational challenges in digital servitization; (3) contextual factors which hinder digital servitization; and (4) available support for digital servitization.

Having identified the challenges related to digital servitization aimed at sustainability across different industrial sectors in Studies B, C D and E; this research incorporated transition into the perspective of requisites. The intention was to evolve knowledge into a proactive perspective in which Sustainability-as-a-Service can be proposed and developed for industrial contexts.

4.7.2 RQ2: What are the requirements for Sustainability-as-a-Service?

Servitizing sustainability, means that a company develops an offering in which sustainability is a main source of value, which it delivers it through service-based business models (Yang & Evans, 2019). This demands a major transformation away from traditional business models whose an offering is product-centred and which covers a customer's needs through mainly tangible products (Blüher et al., 2020).

As with any business transitions, companies need to equip themselves and their collaborators with the right tools, skills and mindsets before changes can capture the value they intend. This research question aimed to categorise the dimensions within which companies must prepare and describe the requirements based on empirical and theoretical findings of this research. This is done by extracting evidence from Studies B, C and D and synthetising them in Study E (which was then evaluated empirically in Study F). The rationale of this synthesis includes the assumption that missing and challenging perspectives identified can be avoided by covering those industrial needs beforehand and conceptualises this concepts transformation as requirements.

The answers to this research question are summarised in the four categories presented in Table 5, which include: (1) technical and economic requirements; (2) organisational requirements; (3) contextual requirements; and (4) support for transition to Sustainability-as-a-Service. This last category includes the framework proposed in Paper 5, with four dimensions: overarching elements, value chain, company and stakeholders. Further, each of the dimensions includes elements that can be transformed into actions that companies are required to consider if they plan to adopt digital servitization.

The next chapter expands and discusses the analysis on the significance of the answers generated through the studies and papers to address the research questions.

5

"Your reward will be the widening of the horizon as you climb. And if you achieve that reward, you will ask no other."

– Cecilia Payne-Gaposchkin

DISCUSSION

This chapter positions the contributions of this thesis in relation to previously existing research. Then, it presents the relationships between research questions, papers and their contributions. Further, it discusses the answer to each research question. Then, it presents reflections on the contributions of this thesis. Further, it presents reflections on the followed research methodology. Last, it suggests possible future research avenues.

5.1 POSITIONING THIS RESEARCH IN RELATION TO PREVIOUS WORK

The global drive that is pushing industry towards becoming more sustainable is urging for companies to explore new business models, in which service-based paradigms can benefit from the digital transformation (Opazo-Basáez et al., 2018). The transformation towards servitization is a change that has been discussed in the literature for many years now (Paschou et al., 2020). Servitization has been drastically accelerated by the "data revolution", with industry having more access to data now than ever. This is enabling new ways of feeding different processes across the lifecycles of offerings.

The results of this thesis are relevant to this field, as they explore challenges from the perspective of practitioners. Research into digital servitization has often been criticised for a lack of documented case studies. However, the case studies in this thesis shed light to different aspects of firms in which servitization is a business model still under consideration, or under testing. The first step to enabling a transformation is to understand the as-is status of the desired object of transformation. Therefore, this thesis evaluates the challenges that hinder the process of digital servitization from different perspectives, assuming that sustainability is the main desired outcome of this work. Furthermore, this thesis has identified requirements for digital servitization. In some cases, these were translated from the concerns and risks in the studies, plus and the corresponding mitigation activities suggested for addressing them.

5.2 DISCUSSING THE RESEARCH QUESTIONS

This subsection discusses the implications of the answers to each of the research questions.

5.2.1 The challenges of digital servitization for sustainability

The transition towards servitization and digitalization is multi-dimensional and complex, posing many challenges to companies and their value chains across different dimensions in the organization. In this research, the identified challenges have been categorised to ensure that as many areas as possible are covered. The selected structure matches the categories proposed in Paper 5, as it provides a structure to which can potentially transform challenges into elements that support the digital servitization transformation. The transformation of challenges into success factors, or opportunities has been a recurrent perspective throughout this research journey.

Initially, Paper 1 examined the challenges of product-service systems and digital technologies. The authors have encountered challenges since the beginning of the literature review process, where the lack of terminological consensus strengthened by the rapid growth of this research stream in the last decades (described by a semi-linear upward trend in relevant keyword searches), has created conceptual divergence. As mentioned in Table 4, the challenges identified are categorized in: (1) economic and technical challenges in digital servitization; (2) organizational challenges in digital servitization; (3) contextual factors which hinder digital servitization; and (4) available support for digital servitization. The categorisation is presented in this order to simplify the discussion of results that follows.

Economic and technical challenges in digital servitization

The transformation of business models which have sustainability is positioned at their core is a challenging shift in thinking. In this research journey, some of the identified economic concerns included the fact that the shift in risks and responsibilities (when moving from traditional product-centred to service-based business models) has meant the transfer of some financial risks from the users to the providers. Such results were anticipated, as one of the main rationales behind the shift from product to service-centred models, particularly in the beginning of the

PSS literature (Tukker, 2004) included the notion that companies would feel more responsibilities when extending the lifecycle of their tangible assets. However, this can bring risks for companies, as some of the documented cases showed a mismatch between revenue and cost streams, whereby providers that converted their previously product-based offerings into PSS had to find the capital for the solution up-front and faced high-risk contracts (Bressanelli et al., 2018b).

Placing greater responsibilities on the supplier of the value offering seems to add complexity at a time when defining the value of data remains difficult. Indeed, the literature reports it as unlikely that sensors embedded in digital PSS offerings can simultaneously send and receive data, unless the end devices are simple and autonomous (Rymaszewska et al., 2017). The lack of such clear data flows was also deemed a risk in the transition towards business models in which materials are the source of value. For instance, the need for economies of scale when attempting to develop a service-based business model, as proposed in Paper 2. A lack of visibility across the value chain hinders the possibility of commercialising end-of-life resources and loop them back into the beginning-of-life of another product.

This research has also explored the perception of offerings that were further dematerialised. In this sense, the transfer risks that were captured reflected the reality of contracts that could look at aspects such as contract-based services. In these cases, providers expressed concern over financial exposure, given the risk of an early contract suspension by customers when they (the providers) have financed the entire solution in advance. The concerns over the servitization paradox (Brax et al., 2021) are an area that requires future research, as it is critical for companies to be able to prevent mismatches between revenue and cost streams (Rymaszewska et al., 2017). Likewise, this illustrates how other mismatches in servitization could be perceived as, in the literature, the anticipated environmental and sustainability benefits are often perceived as an assumption that cannot be backed up with data.

Another challenge lies in the perceived lack of economies of scale available to develop a service-based business model from the output of a recycling process. There is lack of visibility in the value of certain material fractions and a lack of data from earlier in the supply chain (González Chávez et al., 2020). These would allow a company to plan its anticipated volumes, generated over a given period. In general, there was a perception that successful service-based business models require quantities of data that are not accounted for in terms of required resource-intensity. As observed in Paper 2, data collection, management and preparation conform a strenuous process. These pose challenges for companies who need to be ready to prioritize improvement areas with high potential.

Furthermore, for companies to servitize there is a need for customer acceptance of subscription-based services. This is challenged by a possible lack of engagement in mutually convenient timeframes across partnerships. Also, some service-based offerings represent challenges because capitalisation is perceived to take too long, as observed Paper 3.

Similarly, there is a need for harmonised approaches where new incentive models benefit from efficiency, with the benefits and risks shared across stakeholders. Engaging in costing methods that are incentive-based is considered difficult in connection to data, as there is a lack of methods and frameworks to measure results accurately enough to create a costing method that is considered fair and feasible for all stakeholders. Moreover, measuring results by data collection involves multiple sensor installations. These are considered cost-intensive in industrial sectors in which the main product, unit or entity can become outdated. Although this challenge was mainly perceived in the maritime sector, Paper 3, it could be faced in other industrial scenarios.

A similar challenge has been observed in the machine tool industry, which requires sensor installation and retrofitting for digital services to be delivered. This issue is highly complex as, if taken lightly, equipment installation and upgrading could backfire and thus feed the sustainability paradox of servitization. This challenge highlights the need for a proper technological roadmap to be in place before such decisions are taken, thus ensuring that such improvements are sustainable in the long term and consistent with a firm's future innovations.

Thus, in Paper 1, the authors identified technical concerns in the literature regarding the value of data. The idea of delivering data as part of the value proposition is challenged by the need to develop correct visualisation and have the right guidance and understanding of how to use data (Stark et al., 2014). It is also highly complex when connected across supply chains, as it is necessary that companies involved have similar levels of digital maturity (Bressanelli et al., 2018b). Otherwise, there is a risk that some companies will not have the necessary maturity and IT infrastructure to capture value from the services that are designed and offered (Paper 4). Addressing this challenge is of utmost importance, as the potential impact on the sustainability of an individual organisation is incomparable with the possibilities when complete value chains are engaged.

Furthermore, there were plenty of concerns from a data perspective, which included the quality, reliability and availability of data. This is further impacted by the openness towards data-sharing strategies, as failing to share data across a value chain can lead to task replication and the overuse of sensors, which creates digital waste (Aspara et al., 2011). Moreover, a recurrently identified challenge was the compatibility and interoperability of systems, software, and physical equipment, as observed on Paper 3 and 4.

Organisational challenges in digital servitization

Digital servitization presents challenges that can also be organisational in nature. For instance, some of the research indicates that on the demand side, some customers have a "service-for-free attitudes", meaning they may be unwilling to pay additional costs for services (Coreynen et al., 2017; Ulaga & Loveland, 2014). This can make service pricing extremely challenging and poses a problem that has yet to be resolved.

Overall, companies need good digital infrastructures, characterised by high degrees of autonomy, strong human-centredness and available skilled employees who can develop and provide highly complex products (Lerch & Gotsch, 2015). Assessment methods are suggested in the literature, to ensure that companies are ready to perform in this regard (Süße et al., 2018), This is due to a core challenge in that company employees need technical and social competencies (Alghisi & Saccani, 2015; Ardolino et al., 2016).

Challenges in this category included a lack of exploration of supply chain collaboration (Olaniyi et al., 2018; Rivas-Hermann et al., 2015), a lack of supply chain visibility (Norden et al., 2013), cultural integration, a lack of consultation and negotiation procedures and a lack of documentation and capture of knowledge and experience (Alderton & Winchester, 2001). When working with a supply chain, there is a natural element of variability among the sizes of companies. It was noted that some smaller firms often do not have the capacity to engage in large partnerships and require support from research projects and other incentivising ecosystems (Lind et al., 2021).

Furthermore, cultural barriers to accepting change, can mean that service providers will need a better definition of value if they are to avoid unreceptiveness towards their services. Other relevant challenges are the hardships around digital maturity and organisational factors such as loyalty and integration among companies. Overall, there is a need for strategy-focused leaders who can prioritise the transformation of customers mindsets.

Across value chains, there is also a critical lack of employees with the right skills for the handling, management and maintenance of digital devices. Talent retention is a challenge and companies should consider changing their learning programmes to upskill employees. This research has found that small trainings every three or four months are preferred over extended periods of training, as identified in Paper 3. In this sense, human resources should be involved in recruitment and upskilling activities. These should address the skills shortages caused by global circumstances,, such as the challenges remaining after the COVID-19 pandemic and particularly those connected to know-how regarding modelling, data analytics, data analysis and machine learning algorithms (Sassanelli et al., 2022).

Contextual factors which hinder digital servitization

The sharing economy has been widely promoted due to its sustainability potential. However, when integrating physical assets with digital technologies, policy makers need to consider negative perceptions and potential challenges related to the use of IT (Curtis & Lehner, 2019; Fargnoli et al., 2018; Rymaszewska et al., 2017). This is particularly so because, in the studies that were conducted, compliance with regulations seemed to be a strong driver for organisations seeking environmentally beneficial options (Lister et al., 2015; Stevens et al., 2015). This was observed in both Study B and Paper 4.

In this sense (and as mentioned above under organisational challenges) different levels of digitalization between stakeholders and potentially having too many stakeholders, can hinder data visibility across value chains and could potentially limit new digital services. To add to the complexity, there is still a lack of clarity from a legal standpoint on how to address the responsibility for decision-making, as it could create high-risk resolutions (such as influencing the navigation of ships in Study C). This highlights the challenge posed by the perceived need for standards (currently missing) to regulate sector-specific servitization and to some extent, incentivize it, as seen in Paper 4. This is partly because many current industrial actors are questioning the effectiveness of regulatory regimes.

Furthermore, the companies involved in the studies often perceived often lack of loyalty, and integration, with high-set cultural barriers posing a risk to change. Unsurprisingly, the word *trust* was repeatedly encountered in this research (González Chávez et al., 2022). This appears to be an ever-more relevant topic in the data transformation currently being experienced by industry.

Available support for digital servitization

This research has identified conceptual divergence around terms and definitions relating to servitization or PSS. Likewise, the level to which sustainability is integrated in frameworks and methods that claim sustainability-orientated results was evident from their lack of embedded sustainability KPIs. To this extent, and as described in Paper 5, there is still room for new methods and frameworks; ones with a better balance between quantitative and qualitative integration, digital support, more specific descriptions, increased involvement of KPIs, consideration of external factors and validation across different industrial sectors. Such methods and frameworks could particularly benefit from a new addition connecting the different perspectives of value within the stakeholders (Erkoyuncu et al., 2019).

5.2.2 Requirements for Sustainability-as-a-Service

Based on the challenges discussed above, this subsection further elaborates on the requirements for Sustainability-as-a-Service and their practical implications.

Economic and technical requirements

The many economic and technical challenges identified in 5.2.1 highlight the need to identify new revenue streams through strong value propositions. In this sense, there is a requirement to explore alternatives, such as commercialising flexibility, using digital technologies to create competitive advantage through visualisation, creating procurement integration and identifying the value of data, identifying duplication of work. Also, it is required to better use technologies such as AI to support data analysis, adopting predictive maintenance and remote diagnostics and developing capabilities for updating software. These requirements can support with the alignment of product and service lifecycles.

The results (Paper 4) also highlighted the need to analyse configurations of manufacturing environments and provide diverse options and the need to involve maintenance managers in technology investment decisions and implementation. Furthermore, it is necessary to define follow-ups to identify and implement improvements. Among the most relevant requirements identified, is the need to define activities aimed at understanding which are the prerequisites of infrastructures before making investments and support partners in the updates and adjustments of their IT infrastructures. Addressing risks through mitigation activities and planning accordingly before making investments can have a major impact on the perceived paradoxes that cause economic and environmental backlash.

Organisational requirements

From an organisational perspective, there is a need to address data silos which hinder integration across organisations (Paper 3). Also, there was a strong focus on the need for increased collaboration, but this is not possible without loyalty and integration across collaborating companies.

Paper 4 highlighted the need to develop capabilities across the organisation which make it possible to capture knowledge. For instance, there is a requirement to increase audit documentation, interoperability matches and standards at clients' facilities before implementing new services. Furthermore, having skilled employees will be a constant requirement for innovation in the many transitions and transformations that manufacturing and other industrial sectors undergo. Moreover, at organizational level it will be a must to define what are the win-win situations in the digital servitization process. Mutually beneficial offerings are often seen as proposed in the literature, but they are not disseminated on an industrial level.

Lastly, Paper 5 highlighted the need to have trust in institutions and product-services, this can be built through competence development, openness, reliability, communication, empathy and support, transparency and timely data sharing. In Study F, the interviewees reflected on the relevance of complying with organisational requirements so as to have successful transformations. This was because they often highlighted the readiness and major availability of digital technologies and emphasised the need to thoroughly consider the human aspect.

Contextual requirements

Regulations and compliance have repeatedly been named as a driver, which can be transformed into a requirement to achieve digital servitization (Papers 2 and 3). Also, connected value chains indicate strong requirements for good digitalization levels across collaborating stakeholders.

In considering contextual requirements, one might mention a general culture (which needs to be permeated by openness) aimed at data-sharing across value chains. Identify environmental requirements and create value propositions that help satisfactorily cover them. In Paper 4, the main contextual requirements addressed the concerns from a digital security perspective, which includes predefining data ownership structures. Furthermore, Paper 5 highlighted the need to

consider context as new regulations and changing geopolitical situations drastically influence the environment in which companies must perform. Study F emphasised this matter even more, by mentioning the transition that the interviewees perceived in relation to a stronger sustainability focus by many of the firms they collaborate with. This was due to the pressing changes in regulations and increased openness to new business models as such solutions have become disseminated in today's market.

Support for transitioning towards Sustainability-as-a-Service

The work in this thesis has been a continuous exploration of the state-of-practice across several case studies and has followed up on the developing state of theory through literature reviews (González Chávez et al., 2021). The support for transitioning towards Sustainability-as-a-Service represents the main outcome of this thesis, with the developed framework that can provide holistic guidance to many stakeholders.

The main contribution from Study G is the categorization of the findings from the studies conducted (in Paper 2, 3, and 4) through a framework-building process. This led to the proposal of 4 main dimensions, as described in Paper 5: overarching requirements, value chain requirements, company requirements and involved stakeholders.

As part of the interviews performed to evaluate the proposed framework, the experts brought light to the lack of existing support for the adoption of digital servitization in industry. The guidance of industrial companies towards Sustainability-as-a-Service will require awareness of the existing offerings portfolios to identify those offerings that can benefit the most from embedding a servitization approach. Some reflections stemmed from the uniqueness in each transition journey, which can take advantage of tailor-made support to ensure all elements of the shift towards Sustainability-as-a-Service are considered. Also, the interviews highlighted the unique value of having sustainability as an embedded factor of this proposed paradigm.

5.3 CONTRIBUTIONS OF THIS THESIS

This thesis contributes to the body of literature on digital servitization and sustainability by identifying the challenges industry faces in this transition. Moreover, it addresses the conceptual dispersion identified as a challenge in this field and contributes to the systematisation of terminologies related to digital servitization and sustainability, by conducting literature reviews and empirical studies which gathered insights from different schools of thought (González Chávez et al., 2021). For instance, the thesis integrates research that uses PSS as a main keyword, as well as work which refers mainly to servitization as a transformation of the complete business model, rather than purely the offering from a tangible perspective. Furthermore, it brings light to the essential role of digitalization as both an enabler and a driver of new business models and it highlights the relationship with the concept of sustainability as a main industrial goal.

Several authors have addressed the high potential that lies at the intersection of servitization, digitalization and sustainability (Hallstedt et al., 2020; Pirola et al., 2020). Some have also extended this perspective to explore how does digital servitization support some circular economy principles (Bressanelli et al., 2018a) and productivity objectives (Opazo-Basáez et al., 2018). However, this conceptual overlap highlights a research topic which requires further development and increased empirical evidence to further develop theory. Therefore, building on the field of digital servitization with a sustainability perspective provided a focused theoretical contribution.

The relationship between digital servitization and the achievement of sustainability benefits requires embedding sustainability principles as inherent and key elements of new value

propositions in new business models (Paiola et al., 2021). This becomes particularly relevant in the paradigm proposed in this thesis, “Sustainability-as-a-Service”, which is set to enable sustainability unprecedented performance in diverse industrial sectors. The work shown in this thesis illustrates requirements for Sustainability-as-a-Service in industrial scenarios, as presented in Paper 5, with industrial cases from refrigerator recycling, maritime shipping and the machining industry. This thesis takes a proactive approach by transforming the identified challenges for the adoption of digital servitization. It considers them missing elements in the priori system and advances them into requirements which can avoid previously encountered pitfalls and enable Sustainability-as-a-Service.

The exemplification of requirements and challenges responds to the recurrent call from literature, which has highlighted the lack of available industrial cases (Marcon et al., 2022) that reflect on how can this transformation be made. The state of industry is one in which digital servitization still seems a business model that is well out of reach for many companies; they consider it risky and face many of the challenges presented and discussed in this thesis. Therefore, this thesis highlights that the successful advancement of digital servitization will require an iterative process of identifying external conditions and challenges, as well as attempting to cover requirements and further observe the progress and repeating the process iteratively (Xie et al., 2023). The positioning of sustainability at the core in industrial cases is much needed in the research conducted to date, and this thesis proposes to do so through the paradigm of Sustainability-as-a-Service.

From an empirical perspective, this thesis contributes to the state of practice by providing a picture of the current challenges across cases from different industrial sectors. It is uncommon to find research that has worked across such different industrial contexts. In this work, the author was able to explore industrial scenarios with high potential and industrial relevance. The cases included: the recycling industry particularly for e-waste (a highly relevant topic in an era of lac of semiconductors and limited material resources required for the advancement of engineering and manufacturing); the maritime shipping industry (which enables 90% of global world-trade), the machining industry (an ever-relevant industrial sector responsible to enable manufacture of many commercial goods) and even the fashion industry (included in findings of Paper 5). This rich combination provides value and can be seen as a contribution with two aspects. On the one hand, it did not provide such deep sector-specific insights or searched for exhaustive generalisation in a particular industry, but on the other, it shows that there can be some generalisation as many challenges were repeated across sectors.

Furthermore, the approaches followed in this thesis can provide value and guidance to industrial practitioners. From a methodological perspective it benefitted from the use of several approaches to gather insights, which included the combination of strategy-orientated frameworks, single and multiple case studies, the use of risk assessment matrixes to evaluate service offerings. This unique combination is not much found in the literature, it was deemed useful for the intended purpose and contributes to the exploration of future research avenues. Moreover, the results of this thesis can support companies as they prepare to adopt Sustainability-as-Service, as the identified requirements provide guidance on how to set the stage for this transition.

5.4 METHODOLOGICAL REFLECTIONS

Although this research provides several contributions to the emerging body of digital servitization, there are some reflections that must be made when interpreting the results. For instance, the qualitative nature of this research produces results whose generalisability could be different if conducted in other environments. As suggested by (Ragin & Becker, 1994) the

present researcher distinguishes between the constraints of qualitative study and case study. Therefore, the cases were defined iteratively. However, there are limitations to case definition as the amount of data and the timeliness of its availability can influence the outcomes. This is particularly so to for this research, as the case studies were performed somewhat sequentially.

As part of the reflections on this research journey, it should be mentioned that the cases were not entirely uniform in definition. On the contrary, they differed somewhat between the studies, in size, scope and context. This researcher acknowledges the discussion that might be sparked by such differences and would point out the point of the complementarity and data-richness afforded by such differences.

Additionally, it is also relevant to acknowledge that through the time this thesis was performed, there was an evolvement of the terms chosen and applied. Also, the nature of the conducted cases studied differed. For instance, Study B, presented in Paper 2 had a rather product-centred approach, as the case revolved around the tangible elements of refrigerators. Further, Study C (Paper 3), included the cases related to the maritime shipping industry, reflected a much stronger approach to servitization within companies that already provide services, or can commercialise use and results. Later, the cases connected to the machining industry were centred around digital services and their potential for sustainability. The sequence of Study C and D allowed to explore servitization, in a first stance, from a perspective of external implications and as a broader phenomenon. Study D allowed to explore the objects where with intended value (developed digital services) and the receptiveness of companies towards digital servitization, to allow for a more complete picture. This transition generated some heterogeneity in the studied cases, but simultaneously, provided a more representative landscape of the current industrial scenario.

The case studies integrated a mix of large companies and SMEs and, although this provides a broader overview of the industrial reality, it also limits the opportunities to generalise the findings for a sector, or a company size. Further research is required to explore the significance of factors that could produce different results under different conditions.

It is worth mentioning that most of the interviews conducted in the case studies were in an online format. The decision to do so, was based on having a broader spectrum of possible participants if the geographical location of the interviewee was not a limitation. However, as a reflection, conducting interviews online brings certain positive and negative aspects to the result. On the one hand, doing interviews online allows the participants to share screen at any point and demonstrate previous work or provide examples. On the other hand, it brings some limitations such as some limited non-verbal cues that can be missed, and less familiarity with the interviewer as opposed to a face-to-face introduction. (Salmons, 2011)

The search for quality in the research process and outcome, which according to Tracy (2010) cannot be separated, benefits from following rules and guidelines that support learning, practicing and striving for perfection. Thus, criteria can serve as a shorthand for the values of a craft. In the scope of this research, this corresponds to the qualitative outcomes of the research journey that has been undertaken. In her work, Tracy (2010) proposes eight criteria for qualitative research: (1) topic worthiness, (2) rich rigor, (3) sincerity, (4) credibility, (5) resonance, (6) significant contribution, (7) ethics and (8) meaningful coherence.

The topic selected for this research was consistently deemed worthy of exploration. This was a judgement born not only of this researcher's deep interest in the subject. It was also noted in the many interactions with industry documented in Studies B, C, D and F. The interviews were often extended because the interviewees found it appropriate to finish their discussions. The positioning of the articles and the feedback from the reviewers repeatedly confirmed this point.

The rigor of this research was considered, through descriptions of the cases in the appended papers and the abundant data from the multiple industrial contexts explored. This data supported the assumption of transferability in the results that were obtained. The cases were carefully selected to represent the industrial context of the companies studied. Although bias cannot be fully avoided, the researcher attempted to be explicit and transparent in the narratives connected to executing the cases and the process of analysis that followed.

From a theoretical perspective, the researcher prioritised rigour by conductive literature reviews which supported a comprehensive capture of the state of the art. The analysis procedures are also carefully described in the methodology sections of the appended papers and summarized in Chapter 3 of this thesis. The rigour of this research journey is expected to generate future research.

The sincerity aspect is embedded in the research through the multiple statements and discussions on the actual potential for generalisability, transferability, plus reflections on the work's contributions. The researcher is aware of the many different structures that could have been followed and reflects on them thoroughly through the lens of context, including, but not limited to time, space and available resources.

The element of credibility in this research is pursued through the rich descriptions, triangulation of results and multivocality. In this research, this element is expressed in the explicit statements about the interpretations of the interviewees who were approached through the case studies. Furthermore, the element of resonance is pursued through the pursuit of generalisations which were justified in the multiple case studies that were conducted and by identifying patterns across cases.

Although the element of aesthetic merit is rather subjective, the researcher has enjoyed the writing process as an activity: it is an art that allowed ideas to be communicated with peers. Thus, finding a significant element to the contribution has been one of the lodestars of this research journey. The frequent feedback, presentations at international conferences and frequent exposure of the work to industrial practitioners leads this researcher to believe that not only this contribution is valuable, but also that the coming years will see this work continued, as it helps address urgent industrial challenges.

Conducting ethical research is part of the nature of human values and this researcher has attempted to maintain privacy of participants data in each case, as explained to them. Moreover, the researcher has always tried to analyse data from a neutral standpoint and ensured that no comments were taken out of context (in, say, the interviews).

The last component documented by Tracy (2010) is that of meaningful coherence. The primary goal of this research work has been to achieve its objectives and thoroughly answer the research questions. To ensure this, the author has exposed the work to feedback whenever possible and included descriptions that are transparent and self-reflective. Although all these elements are of subjective in nature, the author believes that this research journey has allowed a process of growth and learning, plus an increased desire to continue the research journey, develop knowledge and help address global challenges.

5.5 FUTURE WORK

The concepts and frameworks proposed in this thesis require future work to expand and capture the many opportunities that Sustainability-as-a-Service can provide to industry. Further research might advantageously involve engaging with a larger spectrum of industrial sectors. Similarly, it can benefit from including companies that are more advanced in terms of their understanding and adoption of digital servitization. The present studies looked at companies in

which digital servitization appeared a new concept for them, which allowed this research to achieve an understanding of the current state of practice. However, there is still room to expand the collaboration portfolio to learning from the best practices of successful adopters of Sustainability-as-a-Service.

By way of future work, Study F, might be further developed by integrating the evaluation of the proposed framework in Study E (performed through the interviews with industrial experts) to generate a new version of the proposed framework. Moreover, conducting a more extensive and systematic analysis of the literature, could integrate the industrial feedback and help refine the proposed framework of requirements for Sustainability-as-a-Service. There are plans to document the continuation of this work.

Future work could also include the transforming the identified requirements into quantitively measurable indicators. This would represent evolving the framework proposed in Paper 5, to allow for a quantitative evaluation of the requirements suggested, allowing for measurements of readiness or maturity and adopting a more prescriptive approach. Also, evaluating the interconnectedness of companies across a value chain would provide a more holistic picture to the effects of digital servitization on industrial ecosystems.

Furthermore, the implementation of the framework into a new industrial context (one that is undergoing a digital servitization process with sustainability objectives), could allow the creation and documentation of a Descriptive Study II, as seen in Table 1 in 3.3. This would provide additional insights into the field of digital servitization for sustainability and ultimately illustrating and exemplifying the Sustainability-as-a-Service paradigm to further show its potential in achieving dematerialisation and industrial sustainability.

6

“After all, the ultimate goal of all research is not objectivity, but truth.”

– Helene Deutsch

CONCLUSION

This chapter presents the conclusions of the thesis work highlighting its main findings and its contributions to theory and to practice.

The increased urgency surrounding long-term sustainability has led companies to explore new business models that combine increasing digital capabilities with the pursuit of sustainability objectives, from an economic, environmental and social perspective. Digital servitization can be an option for expanding offerings portfolios and connecting entire value chains. However, although applying digital servitization can promote success and potentially increase sustainability, it brings many challenges. Most industrial companies are unclear as to the requirements for digital servitization, where sustainability is at the core of value propositions. This is why this thesis advanced the concept of Sustainability-as-a-Service.

Through (mostly empirical) studies, this research has identified the status of digital servitization in industry. The identified challenges of digital servitization present a steppingstone towards Sustainability-as-a-Service. This research indicates that there is particular concern over shifting responsibilities and the difficulties around the valorisation of data, especially in an industrial setting, where there are varying levels of digitalization, issues of developing trust across value chains and a tendency to arrange organisations in silos. This research also concludes that various industrial sectors find challenges that are transferable and provide valuable insights across cases.

The challenges identified have provided a starting point for defining the requirements of Sustainability-as-a-Service. This research identified a lack of support frameworks and methods that successfully integrate sustainability at the core of a value proposition. This needs to be addressed urgently if the objectives of digital servitization are to be successfully achieved. Consequently, requirements were defined and consolidated with a proposed framework addressing the necessary steps in terms of economic, technical, organizational, and contextual factors. This framework finds its value in the suggested holistic perspective, in which discussions and actions within a value chain and company, plus overarching considerations are simultaneously addressed. Furthermore, the side-by-side positioning of technology enablers and organisational skills, can promote a more seamless business model transition.

The contribution to knowledge of this thesis lies in the advancement of digital servitization for sustainability through empirical evidence about the challenges, risks and requirements in multiple industrial scenarios. The research outcomes can support industrial practitioners in organising their requirements for Sustainability-as-a-Service and moving towards the vision of a sustainable industry in which value is decoupled from tangible assets.

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