THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Sustainability transition of production systems in the digital era

- *a systems perspective for building resilient and sustainable production systems*

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Cover
The cover illustration is a depiction of the different factors that influence the sustainability transition of production systems in the digital era. Created using images from: www.flaticon.com

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ABSTRACT

Locked-in manufacturing industries with highly structured operations and path dependencies are major contributors to the sustainability challenges currently burdening our planet. The effects of the ongoing pandemic, large-scale environmental impacts due to climate change and constant economic and social downturns are just some examples of these sustainability challenges. Increased digitalisation, awareness, global initiatives and regulations are pressuring manufacturing industries to transition towards sustainable development. However, there exists a multitude of interpretations in implementing sustainability in manufacturing industries. This makes proposing tangible actions to translate global initiatives complicated, thus hindering the sustainability transition process.

The purpose of this thesis is to support the advancement of resilient production systems which can overcome sustainability challenges in the Industry 4.0 era. Hence, the thesis aims to investigate: (i) the systemic challenges of manufacturing companies which hinder their sustainability transition process and (ii) the mechanisms by which a systems perspective may be applied to support the transition. A mixed-methods approach was used to carry out the research, using qualitative and quantitative data from three (empirical and theoretical) studies.

Applying a systems perspective helped reveal the challenges which hinder the sustainability transition of production systems. Understanding the production 'system' as a whole (and the underlying web of intricate dependencies and challenges in production operations) required this holistic perspective. Regarding the challenges, it was observed that manufacturing industries across different domains face three main types of challenge: internal (such as organisational routines, strategies and cultural mindset), external (such as regulations and collaboration with stakeholders) and technological (such as maturity levels and data).

Three different enabling mechanisms were explored which may help overcome the above sustainability challenges and support the sustainability transition of manufacturing industries: (1) Industry 4.0 technologies, (2) dynamic capabilities and (3) resilience engineering. It was observed that Industry 4.0 technologies (such as artificial intelligence/machine learning, virtual development tools and sensors) are largely implemented to enable sustainable manufacturing in the form of resource efficiency and waste reduction. The results also revealed five microfoundations of dynamic capabilities – communication, organisation, resources, collaboration and technology. Based on Industry 4.0 opportunities to promote sustainability transitions, the results revealed five industrial resilience factors – robustness, agility, resourcefulness, adaptability and flexibility.

This research contributes to theory by studying the convergence of emergent research topics, such as Industry 4.0, dynamic capabilities and resilience engineering in the context of sustainability transitions. In terms of a practical contribution, the sustainability transitions model developed in this thesis may support industrial practitioners in gaining a holistic understanding of the systemic challenges to sustainability, plus corresponding mechanisms to promote the sustainability transition of industries and the building of resilient production systems.

Keywords: sustainability, industries, manufacturing, production systems, Industry 4.0, dynamic capabilities, resilience

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"Acknowledging the good that you already have in your life is the foundation for all abundance" - Eckhart Tolle. I begin my heartfelt notes of acknowledgement with an earnest prayer of gratitude to Ajja, whose guidance and grace have allowed me to accomplish and stay true to my highest path. Mere thanks to you, Ajja, will not suffice and I hope I continue to make you proud each day.

I embarked on this PhD journey to push my limits as an engineer and contribute to the greater good, with sustainability at the heart of my research. Thank you, Johan, for giving me this opportunity, for believing in my ideas and for encouraging me to believe in myself.

I should like to express my gratitude to my supervisor, Björn, whose guidance helped bring this thesis to fruition. I also wish to acknowledge the support I received from my co-supervisor, Mélanie, whose advice helped me go deeper into my analysis and thought process.

Being a good researcher requires fruitful collaborations and I have been blessed with these in the last two years. Thank you Vinnova and Horizon 2020 for funding me. I am also grateful for the friendships and the experience I gained in Produktion2030's 'Sustainability Analysis of P2030's projects' and 'ReWind' projects, as well as H2020's BOOST and TRUST collaborations. I am humbled to be surrounded by intellectual minds which further my own transformation and it is entirely this support system which enables me to continue on my PhD journey.

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The quote from Sheryl Sandberg, that "finding gratitude and appreciation is key to personal resilience" has resonated with me in both my personal and professional worlds. As with the topic of this thesis, resilience is an all-encompassing term in my life. This PhD journey has its share of highs and lows and is constantly teaching me to become more independent and resilient to the different challenges and experiences along the way. I look forward to starting the next phase of my research and to my individual growth, so that I may contribute to a more resilient and sustainable world.

APPENDED PUBLICATIONS

The following three papers are appended to this thesis (Papers I-III):

Paper I Chari, A., Despeisse, M., Barletta, I., Johansson, B. and Siewers, E. (2020). *Stakeholders' influence towards sustainability transition in textile industries.* EcoDesign conference, Yokohama, Japan.

Paper II Chari, A., Niedenzu, D., Despeisse, M., Machado, C. G., Azevedo, J. D., Dias, R., Bärring, M. and Johansson, B. (2020). *Digitally Driven Supply Chains: A Dynamic Capabilities Approach to Promote Circular Economy and Industrial Symbiosis.* Under review in the International Journal of Production Economics (IJPE).

Paper III Chari, A., Duberg, J. V., Lindahl, E., Sundin, E., Stahre, J., Despeisse, M., Johansson, B. and Wiktorsson, M. (2021). *Practices Towards Resilient and Sustainable Production in Industry 4.0: A Swedish Manufacturing Perspective.* Submitted to ASME's Manufacturing Science and Engineering Conference, Cincinnati, Ohio, USA.

WORK DISTRIBUTION

The work was distributed among the authors of the appended papers as follows:

Paper I Arpita Chari designed the study and conducted the investigation, formal analysis and literature review. She also conducted the interviews, sent out questionnaires and wrote the paper. Mélanie Despeisse provided support in improving the overall structure of the paper and in the review process. Ilaria Barletta conducted the concept-mapping workshop and contributed to reviewing the paper. Björn Johansson reviewed the paper and provided comments. Ernst Siewers provided support in the data analysis and gave feedback to improve the quality of the paper.

Paper II Arpita Chari designed the study and conducted the literature review and expert panel interviews. She also conducted the data analysis and wrote the paper. Denis Niedenzu supported with conceptualisation and data analysis and provided his expertise on dynamic capabilities. He also gave support by reviewing the paper and providing feedback. Mélanie Despeisse contributed to improving the illustrations and reviewed the paper. João Azevedo and Ruis Dias provided case study data for the analysis and helped in the literature review process. They also reviewed the paper and provided feedback on industrial symbiosis. Maja Bärring provided case study data. Björn Johansson reviewed the paper and provided feedback.

Paper III Arpita Chari designed the overall study with Johan Vogt Duberg and Emma Lindahl and, together, they conducted interviews and carried out the survey analysis. Arpita Chari also conceptualised the resilience concept for Industry 4.0 and sustainability, conducted the literature review and wrote the paper. Johan Vogt Duberg supported in creating the graphs and some of the illustrations and co-wrote some sections of the paper. Emma Lindahl reviewed the paper and provided her expertise on circular economy. Johan Stahre reviewed the paper and provided comments. Mélanie Despeisse helped improve some of the graphical illustrations, reviewed the paper and provided feedback. Erik Sundin supported in the survey design and analysis, reviewed the paper and provided comments. Björn Johansson and Magnus Wiktorsson reviewed the paper and gave feedback.

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LIST OF ABBREVIATIONS

I4.0 – Industry 4.0
CE – circular economy
IS – industrial symbiosis
IoT – Internet of Things
CPS – cyber-physical systems
AI – artificial intelligence
ML – machine learning
VD – virtual development
AM – additive manufacturing

"Be the change you wish to see in the world."

– Mahatma Gandhi

INTRODUCTION

This chapter gives the reader a background to the research, alongside its vision and aim. This is followed by the research questions to be addressed and the delimitations.

1.1 BACKGROUND

We live in a world which is largely dependent on manufacturing industries. Almost everything we use in our day-to-day lives has been created or processed in a manufacturing environment. However, manufacturing industries are a major contributor to sustainability challenges as they are highly resource-intensive, energy-intensive and polluting (Pineda-Henson and Culaba, 2004, Horowitz et al., 2018, Jena et al., 2020, García-Muiña et al., 2020). We are also currently in the Anthropocene Epoch, in which human activities have given rise to unprecedented, multi-dimensional and complex environmental challenges, such as climate change, rapid depletion of natural resources and air and water pollution. There are also societal and economic problems, such as supply uncertainties in developing countries, poverty, unequal incomes, poor working conditions, risk of accidents and so on (Markard et al., 2012).

Hence, the need is now more urgent than ever to avert a climate crisis and set the world on a pathway to a sustainable future. If manufacturing industries are to survive and, in turn, impact the survival of society and the limited resources available in our ecosystem, they will need to transform into more flexible and efficient operations, whilst reducing material consumption and environmental impacts. Moreover, to operate within safe planetary boundaries (Rockström et al., 2009), manufacturing industries will need guidance as they transition to more sustainable forms of production and consumption; ones that will affect current and future generations. Thus, the main topic of this thesis is 'sustainability transitions' of production systems. That is, the thesis aims to support manufacturing industries (which have highly structured operations and lock-ins) in moving towards sustainable development.

The Brundtland Report issued by the United Nations World Commission (United Nations World Commission on Environment and Development, 1987), was the first to highlight and popularise the term 'sustainable development' as the ability of the current generation to meet present needs without compromising the ability of future generations to meet theirs. The 'sustainable production' concept was then introduced at the UN's Conference on Environment and Development in 1992, which also related to the concept of sustainable development (United Nations Conference on Environment and Development, 1992). Sustainable development has also served as a guiding paradigm in global policies and practices. Advancements in international policies, such as the UN's Sustainability Development Goals (UNSDGs) (UN, 2015), the EU's recent Green Deal (European Commission, 2019), the EU's Circular Economy Action Plan (Commission, 2015), and the work done by the European Environment Agency (European Environment Agency) and OECD (Organisation for Economic Co-operation and Development) are some examples.

Several conceptualisations of sustainable development have been offered since the Brundtland Commission first popularised the concept three decades ago. For the present context, sustainability is defined as 'the attainment of dynamic equilibrium in realising the optimum value within a socio-technological system with concurrent minimisation of adverse impacts on business, society, ecology, and the environment' (Amadi-Echendu and Thopil, 2020). In this thesis, 'production systems' are considered to be socio-technical systems which encompass both humans and technologies.

Manufacturing industries play a vital role in sustainability transitions, as they implement and develop new technologies and services (Farla et al., 2012). Industry 4.0 or Industrie 4.0 (I4.0), a term used to initiate the Fourth Industrial Revolution, was a high-tech strategy initiated in

the Hannover Messe by the German government in 2011 (Anderl, 2015) to advance German manufacturing. Rapid technological developments in I4.0 have induced disruptive changes in economies, organisational structures and industrial operations (Schwab, 2016). But these developments have been predominantly economic and the long-term implications for the environment and society are still largely unknown.

About two decades ago, Crutzon (Crutzon, 2002) stated in his paper, 'Geology of Mankind', that without the occurrence of a global catastrophe such as a pandemic or world war, humans will continue to be a major contributor to environmental challenges for many centuries to come. However, the recent Covid-19 pandemic has played an unexpected (and quite opposite) role in our fight to address these challenges. Countries like the United States and Canada are aiding the economic recovery of fossil-based industries affected by the pandemic (Markard and Rosenbloom, 2020), instead of channelling those funds toward a low-carbon future.

Hence, building industrial resilience that fosters sustainability has become increasingly relevant in addressing the burgeoning and unpredictable effects of climate change. Although the digital transition in I4.0 is being used to leverage productivity and competitiveness, it may also be an effective means of improving industrial resilience towards sustainability challenges (World Economic Forum, 2020). Hence, if industries are to become sustainable, it will also require the implementation of resilience-thinking in their operations (Zavala-Alcívar et al., 2020).

1.2 VISION AND AIM OF THE THESIS

At the heart of this author's vision are resilient production systems which can achieve long-term sustainability. The author envisages an ideal scenario in which production occurs in a closed loop with zero defects; one in which production systems are resilient to unplanned events and sustainability challenges and digital and sustainability transitions occur seamlessly and in unison.

The thesis will attempt to bring this vision into reality through the twofold aim of: (1) analysing the systemic challenges to being sustainable faced by today's manufacturing companies and (2) investigating the mechanisms that can overcome these challenges and applying systems thinking to support the sustainability transition of manufacturing companies in the digital era.

1.3 RESEARCH QUESTIONS

With the background and vision in mind, the thesis will aim to answer the following research questions:

RQ 1) What systemic challenges do manufacturing companies face when moving towards a digital and sustainability transition?

Despite evidence in the literature of sustainability transition management frameworks, sustainability performance management methods and I4.0 technologies to improve industrial sustainability, manufacturing companies still face several challenges to implementing sustainability. Therefore, RQ1 aims to provide empirical and theoretical evidence for the systemic challenges that manufacturing companies face in their digital and sustainability transition efforts.

RQ 2) What enabling mechanisms can address these challenges and support the sustainability transition of production systems in the digital era?

Several enabling mechanisms may influence the transition of manufacturing industries towards implementing sustainable practices in this digital era. Through qualitative and quantitative studies, RQ2 aims to understand the role of I4.0 technologies, dynamic capabilities and resilience thinking as enablers of the sustainability transition process.

1.4 DELIMITATIONS OF THE RESEARCH

This thesis has the following delimitations:

- A large proportion of the literature describes the concept of sustainability transitions being used primarily to transform socio-technical systems such as food and agriculture, water and sewage management, transportation and so on. In the context of this thesis, however, the concept has been explored at the level of manufacturing industries (factory-level production systems) and their supply chains.
- Several mechanisms might potentially support the sustainability transition of manufacturing companies, but this thesis focuses on enablers which may combat the specifically identified systemic challenges and support the transition process.
- The thesis does not consider the influence of changing demographics, political systems or financial policies governing a sustainability transition process.
- Some of the challenges identified in the thesis might be sector-dependent and may not be relevant to other industrial sectors. This will require future investigation.

1.5 STRUCTURE OF THE THESIS

The thesis has been structured as follows.

The present chapter introduced the reader to the overall objectives of the research alongside the research questions.

Chapter 2 frames this research and presents the theoretical background.

Chapter 3 showcases the author's philosophical worldview and the research strategy which has been formulated.

Chapter 4 illustrates the results.

This is followed by discussions and future work in Chapter 5.

Chapter 6 outlines the summary and conclusions.

2

"The greatest enemy of knowledge is not ignorance; it is the illusion of knowledge"

– Stephen Hawking

FRAME OF REFERENCE

The following chapter seeks to briefly describe the key concepts and theories guiding the research, with particular emphasis on sustainability transitions, Industry 4.0, dynamic capabilities and resilience engineering. The underlying motivation of this chapter is to find a theoretical underpinning and connect these different strands of research to understand how they contribute to industries transitioning towards sustainability in the digital era.

Section in thesis	Connection to RQ
2.1 Sustainability transitions	RQ1, RQ2
2.3.1 Digital transitions in I4.0	RQ1, RQ2
2.3.2 Dynamic capabilities	RQ2
2.3.3 Resilience engineering	RQ2

2.1 SUSTAINABILITY TRANSITIONS

The current, linear mode of production and consumption of several industrial sectors, plus the unpredictable shock of the Covid-19 pandemic, has put a strain on the planet's already limited available resources, causing climate change, biodiversity loss and other grand sustainability challenges (Reid et al., 2010). Various processes may move a system to more sustainable states. In other words, there may be many different transition pathways towards sustainability. These may be transformative, involving fundamental and radical change to the system, or adaptive, with the system undergoing smaller incremental changes (Schilling et al., 2018). The pathways may differ according to varying system goals, boundaries and assumptions and are always context-specific (Leach et al., 2010). As radical transformation is still an underdeveloped research field at the firm level, this thesis also explores resilience engineering theory to study how industries may use incremental methods to move towards sustainability transitions.

Sustainability transitions aim to enhance a system's overall sustainability through political, social and technological interventions (Markard et al., 2012). These transitions are supported and guided by the long-term visions, strategies, resources and capabilities of individual firms and other organisations influencing a firm's transition process (Berkhout, 2006, Loorbach, 2010). Sustainability science, the theory underpinning sustainability transitions, seeks to address the challenges that society and the planet face. It is an approach that entails evaluating current system conditions and the identification of unsustainable areas. Future sustainable scenarios or pathways are then systematically defined, indicators are assigned to those options and specific strategies developed to achieve them (Gibson, 2006, Leach et al., 2010, Smith and Stirling, 2010).

The European Environment Agency (European Environment Agency, 2017) presented an analytical overview of different transition perspectives to respond to sustainability challenges. These included socio-ecological transitions, socio-technical transitions, transitions in socio-economic systems, action-oriented perspectives on transitions and system innovation and integrated assessment modelling approaches to analysing systemic change. This thesis considers the transition of 'socio-technical' production systems.

Socio-technical systems are 'complex multi-dimensional systems combining diverse elements which evolve interdependently, making them resistant to fundamental changes, thus giving rise to 'lock-ins'' (Geels et al., 2017). Production systems are larger systems which encompass manufacturing systems and convert input materials into outputs in the form of finished products, by-products, services and waste streams. Its components include: infrastructure, skills, capabilities and knowledge required for production; suppliers, consumers, end-of-life stakeholders in the value chain of the product life cycle; consumer behaviour, culture and expectations; government policies and regulations; and public investments.

2.2 THE NEED FOR SYSTEMS THINKING

From the 1970s to now, environmental challenges have evolved from linear cause-effect principles towards more complex, multi-causal and systemic principles (European Environment Agency, 2017). Sustainability is also a non-linear dynamic concept (Voulvoulis and Burgman, 2019), which cannot be measured as an end-state (Rotmans, 2006), but should

be represented within transitions by a complex systems perspective (Moldavska and Welo, 2019). Moreover, production systems include an interlinked web of influences and dependent components which cannot be studied in isolation. These elements have a significant impact on the dynamics of the system (Markard et al., 2012), further fuelling the need for integrated, systemic approaches to facilitating sustainability transitions.

2.3 ENABLERS OF SUSTAINABILITY TRANSITIONS

The literature reveals that successful sustainability transitions of manufacturing industries are supported by several enablers: technology and eco-innovations (Farla et al., 2012); monitoring methods (Taanman, 2014, Voulvoulis and Burgman, 2019); financial policies (Speck and Zoboli, 2020); firms' existing and new dynamic capabilities (Teece et al., 2016); and multi-actor interactions (Farla et al., 2012).

The action plan proposed in the EU's Green Deal (European Commission, 2019) also describes some of these enabling mechanisms towards sustainability transitions. The Green Deal aims to tackle environmental challenges within the EU and achieve a successful transition towards a sustainable, climate-neutral future by 2050. This will be especially significant for manufacturing and require a major overhaul of many aspects of the economy. Some of the mechanisms proposed to enable this transition are: building climate and environmental resilience; developing new technologies, disruptive innovations and sustainable solutions; unlocking the benefits of digital transformation (data-driven innovation) to support the ecological transition; identifying industrial sustainability impacts; and the proactive acquisition of skills to benefit from the transition.

Using the supporting literature and the Green Deal's action plan, three specific enablers were explored to overcome the specific sustainability challenges identified in this thesis and support the sustainability transition of manufacturing companies: Industry 4.0, dynamic capabilities and resilience. These are conceptualised below.

2.3.1 Digital transitions in Industry 4.0

The world has undergone three major industrial revolutions: the First Industrial Revolution (c. 1760-1840), which involved a transition from manual production methods to the use of steam and water power; the Second Industrial Revolution (c. 1870-1914), which introduced the modern production assembly line alongside the use of electricity, gas and oil and brought a period of great economic growth; the Third Industrial Revolution in the latter half of the 20th Century saw the use of electronics, communications and computers in production processes, the emergence of nuclear energy and two major inventions: programmable logic controllers (PLCs) and robots. This period was also known as the Digital Revolution.

The current industrial revolution, the Fourth Industrial Revolution or Industry 4.0 (I4.0) builds on the Digital Revolution, in which machines, humans and supply chains are connected via the Internet, giving rise to cyber-physical systems (CPS) (Blunck and Werthmann, 2017). An emerging paradigm, it brings together the physical and virtual worlds in a holistic environment (Zhou et al., 2016). I4.0 has evolved at an exponential pace compared to the previous revolutions and has brought technological breakthroughs in the form of collaborative robots, the Internet of Things (IoT), blockchain, big data analytics, simulation models and digital twins, artificial intelligence, additive manufacturing or 3D printing, edge computing and so on.

These disruptive technologies have been considered radical innovations in I4.0, giving rise to a reconfiguration of companies' economic value (García-Muiña et al., 2020). Recent research has also showcased the potential of Industry 4.0 technologies to provide opportunities for the sustainable transition of industries (Dassisti et al., 2019, Bag et al., 2020, Bakkari and Khatory, 2017, Berawi, 2019, Blunck and Werthmann, 2017, Bonilla et al., 2018).

It is anticipated that the digital transition due to technology implementation in Industry 4.0 will transform industrial operations, producing positive sustainability implications. Among many other advantages, these include: circular economy benefits (the use of functions/services instead of products, popularly known as Product-Service Systems (PSS) (Charro and Schaefer, 2018, Devos and Masek, 2017); the creation of business models which reuse and recycle waste (Nascimento et al., 2019)); and the improvement of eco-efficiency, waste reduction, sustainable value creation opportunities and enhanced working conditions (Müller et al., 2018, Bonilla et al., 2018).

2.3.2 Dynamic capabilities

For rapidly changing environments, Teece et al. (Teece et al., 1997) explain that dynamic capabilities are those that give firms competitive advantage. They determine how organisations build their competences and the effectiveness of these capabilities is largely dependent on existing organisational parameters. The 'dynamic' aspect refers to changing market conditions and the accelerating pace of innovation, while 'capabilities' refers to the 'sensing', 'seizing' and 'transforming' of skills and resources within the firm. These capabilities are, in turn, supported by 'microfoundations' (Teece, 2007); these are unique to individual firms, making it difficult for competitors to adopt them.

Considering the resource-based view of firms, it may be said that the effective management of organisations' available resources and capabilities can give rise to sustainable competitive advantage (Penrose, 1995) and enhance the sustainability performance of industries and supply chains (Amui et al., 2017, Bag et al., 2019, Beske et al., 2012, Cezarino et al., 2018). Moreover, the capabilities of I4.0 technologies may extend these existing resources and competitive advantage (Eikelenboom and de Jong, 2019, Felsberger et al., 2020, Garbellano and Da Veiga, 2019, Gupta et al., 2019, Gupta et al., 2020), thus enabling the sustainability transition process.

2.3.3 Resilience engineering

Fundamentally transformative strategies in sustainability transitions generally require the reorganisation of organisational structures and involve substantial risks, uncertain outcomes and associated costs (Redman, 2014). Although radical transformations may bring about 'new normal' competitive conditions, incremental strategies such as resilience may help restore existing functions and build robustness of firms by adapting to unpredictable events along transition pathways.

The concept of resilience was formally introduced in the 1970s in the field of ecology, with Holling (Holling, 1973) defining it as '*a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables'*. Resilience engineering, the theory that underpins resilience, states that systems may gradually withstand shocks, overcome challenges in transition pathways and reach sustainable states by building adaptive resilience capacities.

Previous research has showcased that industries and supply chains who incorporate resilience management strategies may further improve their sustainability performance (Zavala-Alcívar et al., 2020). As described above, sustainability should not be considered an end in itself but a fundamental characteristic of systems that are dynamic and continuously adapting to changes along transition pathways (Ates and Bititci, 2011).

Since economies are based on worldviews in which change and growth are inevitable, industries should embrace the resilience concept if they want to be competitive and contribute to sustainability. Previous studies have also shown that resilience and, in turn, the sustainability of manufacturing companies may be enhanced by implementing I4.0 (Amadi-Echendu and Thopil, 2020, Amjad et al., 2020, Kumar et al., 2020). This will be explored in the thesis.

2.4 CONCEPTUAL RESEARCH FRAMEWORK

IDEF0 is a widely-used standard method of functional modelling developed by NIST in 1993 for the structured analysis and design of the different decisions and activities of a system (National Institute of Standards and Technology (NIST), 1993). It helps establish the scope of an analysis through a graphical representation of the different functions to be carried out. It was also created as an effort towards 'system' development. The IDEF0 model was used to formulate a conceptual research framework to guide the present thesis. Since the thesis incorporates a systems-thinking perspective, the use of the IDEF0 model in developing the framework was further supported.

In a top-level context diagram of an IDEF0 model, functions or activities are depicted in boxes. Interface arrows 'control' and 'enable' those activities, alongside inputs and outputs in the system. Figure 1 shows this top-level representation of the model. IDEF0 modelling also entails decomposing the various activities into sub-functions or child diagrams. Since the idea was to provide a general description of the functions, scope and boundary of the thesis, this level of decomposition was not required.

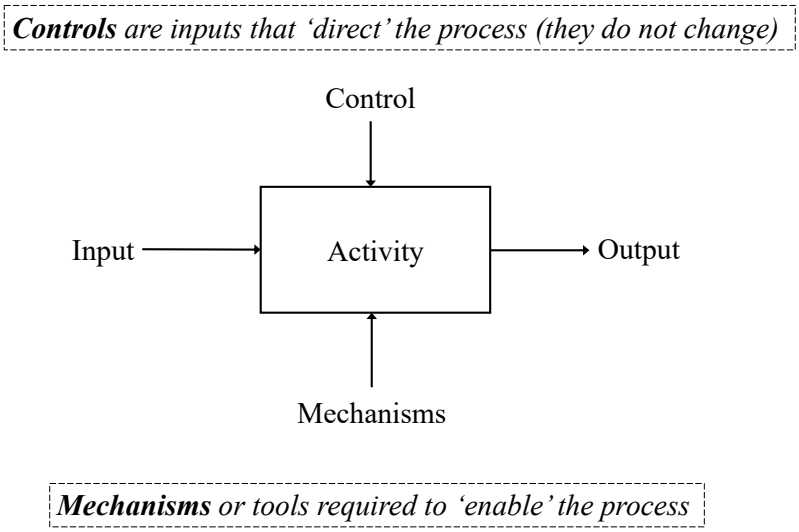

Figure 1. Top-level context diagram of an IDEF0 functional model (National Institute of Standards and Technology (NIST), 1993).

Connecting the different aspects of the model to the thesis, the 'activity' is the sustainability transition of production systems and the inputs that 'control' (and are limited to) this function are governmental regulations, international policies, environmental challenges and unpredictable events. The 'mechanisms' or tools that enable the sustainability transition activity are: the enabling technologies of I4.0; dynamic capabilities theory; and resilience engineering theory. The main input to the system is unsustainable production systems and the output is the achievement of sustainable production systems.

Relating these concepts to the multilevel perspective (Figure 2) of sustainability transitions research, unsustainable production systems were depicted as dominant 'regimes' (unsustainable system states) which resist sustainability transitions (towards higher sustainability system states).

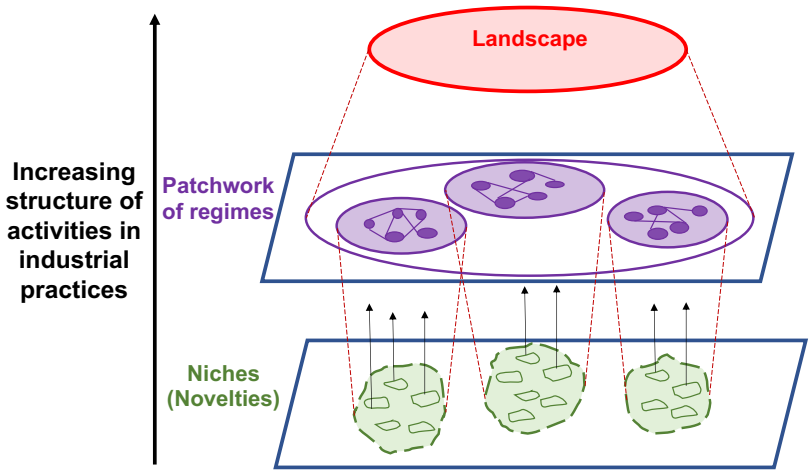

Figure 2. Nested levels of the multilevel perspective framework (modified from (Geels, 2002) (Paper I)).

These regimes have lock-ins that prevent necessary adaptations and dominant structures and configurations that stabilise current system states. The enablers of sustainability transitions were considered to be 'niche' innovations which enable the sustainability transition process. Niches are considered to be protected spaces in transition studies, within which radical innovations may develop. The factors controlling the sustainability transition were considered part of a 'landscape' environment. This landscape helps open windows of opportunity for niches to make fundamental changes within dominant regimes and pressures them to transition towards more sustainable operations.

These sustainability transition concepts were embedded in the conceptual framework that guided this thesis and are shown in Figure 3.

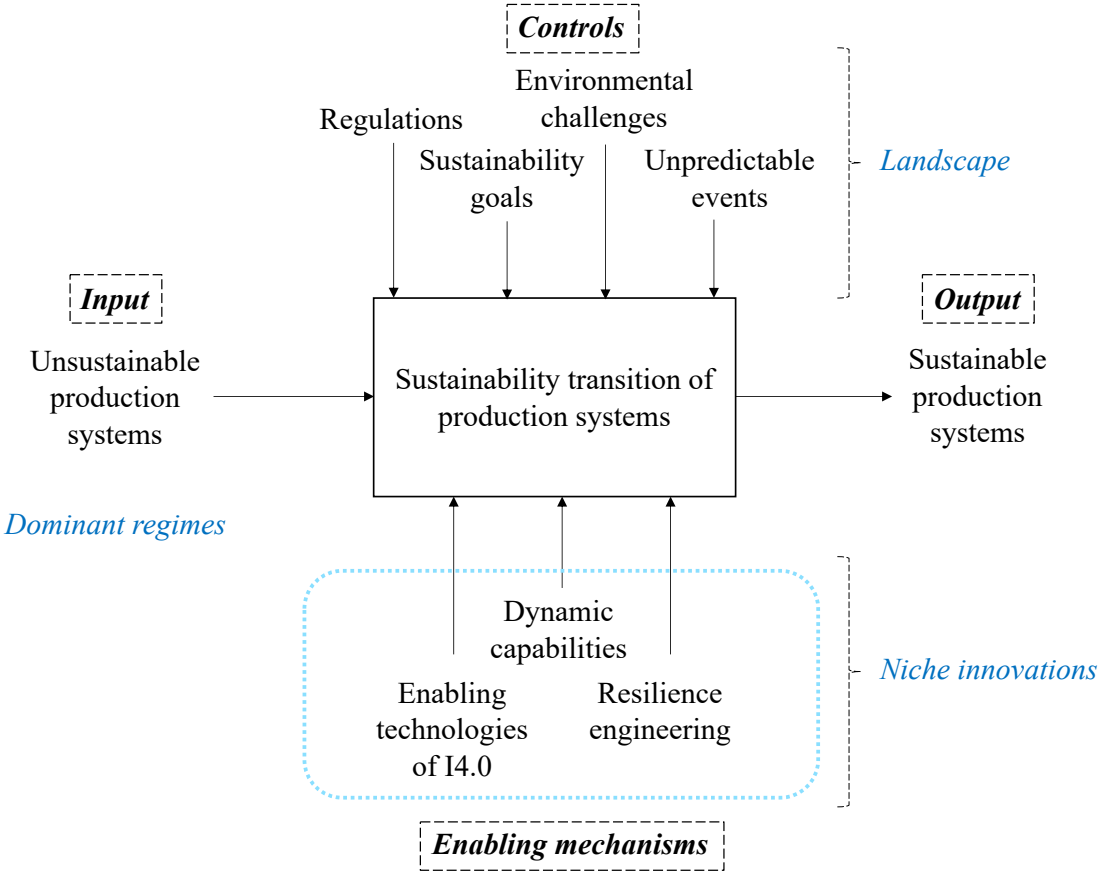

Figure 3. Conceptual research framework that guided this thesis.

A brief overview of the different concepts used in the thesis is given in Table 1.

Table 1. Definitions of the different concepts used in the thesis.

Concept	Definition
Sustainability in socio-technical systems	'The attainment of dynamic equilibrium in realising the optimum value within a socio-technological system with concurrent minimisation of adverse impacts on business, society, ecology, and the environment' (Amadi-Echendu and Thopil, 2020)
Resilience in the context of socio-technical systems	'The systemic capabilities of socio-technical systems to accommodate the effects of change stressors' (Amadi-Echendu and Thopil, 2020) and to 'survive, adapt, sustain and equip the business in the face of turbulent change' (Ates and Bititci, 2011)
Robustness	'The extent of extraordinary change (in behaviour, functionality, and performance) that the socio-technological system can exhibit'(Amadi-Echendu and Thopil, 2020)
Agility	'The capability of a firm to be quickly responsive when dealing with turbulence' (Conz and Magnani, 2020)
Resourcefulness	'The capability to accumulate different diversified assets and resources - financial, physical, human, technological, organisational and reputational' (Pal et al., 2014)
Adaptability	'The capability to adjust the firm's response and to adapt internal processes to changing external conditions' (Folke et al., 2002)
Flexibility	'The capability to implement rapid decision-making processes, quick internal communication and fast learning to quickly adapt routines and strategies to changing conditions' (Pal et al., 2014)

3

"Science progresses best when observations force us to alter our preconceptions"

– Vera Rubin

RESEARCH APPROACH

This chapter describes the author's philosophical and theoretical standpoint which underpin the approach, design and methodology of her research.

3.1 PHILOSOPHICAL FOUNDATION & THEORETICAL BACKGROUND

A researcher's values and ethics can play an important role in effecting a significant change in society, however small it may seem at the beginning. My cultural beliefs and academic background prior to embarking on this PhD journey have largely influenced the relationship between my research philosophy and the investigative process carried out in my research.

My ethical standpoint stems from my cultural background in which we worship the Earth and all of its bounty. This, in turn, places my perspectives in an 'ecocentric' low-substitutability view of strong sustainable development: that Nature's capital cannot be replaced by man-made capital and that we must strive as much as possible to restore what we extract from Nature.

Based on the fundamental assumptions of the ontological (one's view of the world) and epistemological (how one gains knowledge from the world) debate (Burrell and Morgan, 1979), I initially began my research process with a positivistic view; in other words, objectively observing phenomena as much as possible to create meaning and gain knowledge. However, I soon realised that it was impossible to disregard the subjective influence of humans in the sustainability transition process. This was because no systems in my study are purely technical; they always involve humans. I also realised that the various studies I was involved in used multiple data-collection methods to meet project objectives. Hence, I position my philosophical view of the scientific world using the pluralistic realities of the 'pragmatic' approach (Creswell, 2003, Creswell and Clark, 2007).

The pragmatist worldview ("a basic set of beliefs that guide action" (Guba, 1990) p. 17) allows researchers to choose between a range of methods that work best for the situation at hand, making it practical (Creswell, 2003, Creswell and Clark, 2007) and allowing for the inclusion of subjective and objective values and facts (Saunders et al., 2019). It also gives the researcher the freedom to focus on the research problem or question, rather than the method. The emphasis of my research is to provide industrial decision-makers with practical solutions to enable the sustainability transition of socio-technical production systems in the digital era, which further cements the use of a pragmatic approach.

3.2 RESEARCH DESIGN

This section will briefly explain the overall research design of the thesis and then describe in detail the different methods underpinning the studies which were conducted.

Crotty's conceptualisation (Crotty, 1998) was used to position my philosophical worldview within the research approach and is shown in Figure 4. It consists of four components: my philosophical worldview, the theoretical foundation built on this worldview, the research methodology and the data-collection methods used in the different studies.

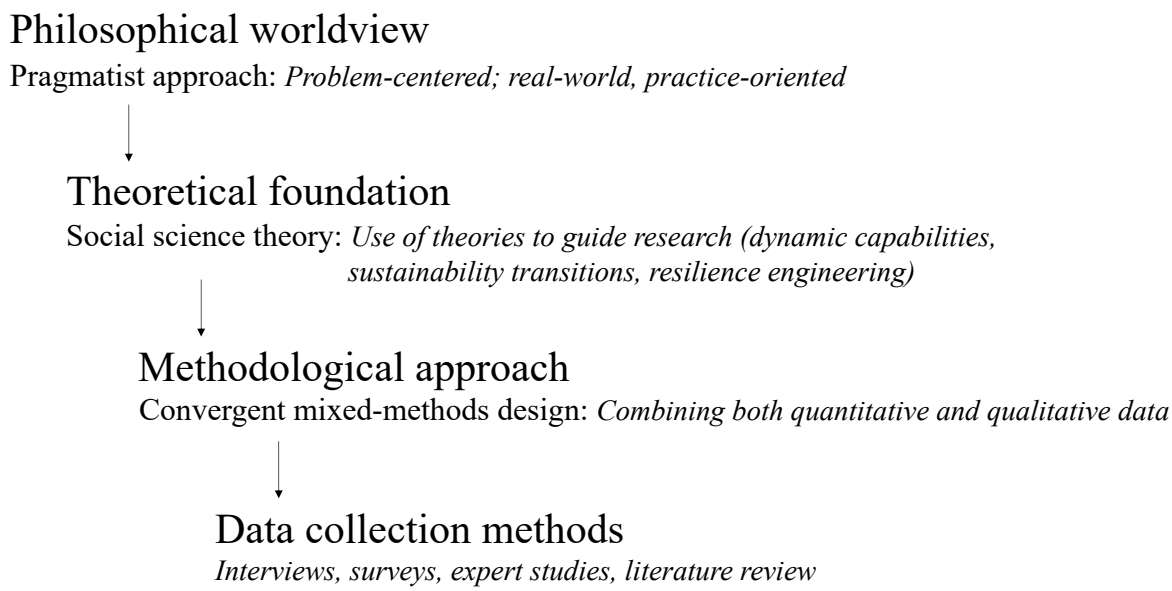

Figure 4. Research approach used in this thesis (Creswell and Clark, 2007, Crotty, 1998).

Three studies were conducted between early 2019 and late 2020, to answer the research questions. The different studies and the paper outcomes during this period are depicted schematically in Figure 5. Details of the research design and the methods followed for the papers are elaborated upon in Table 2.

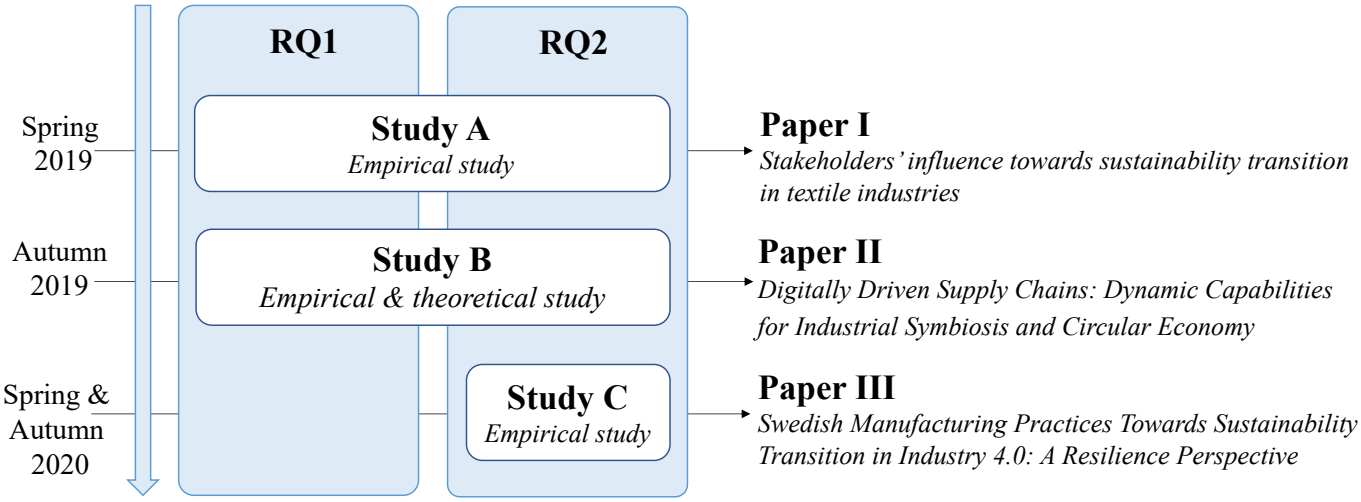

Figure 5. Studies and paper outcomes.

Table 2. Research design and methods adopted in the different papers.

Study	Paper	RQ1	RQ2	Research Design	Data Collection	Data Analysis Method
Study A	Paper I	x	x	Case study	Interview, literature	Explanatory, theory-consuming & prescriptive
Study B	Paper II	x	x	Multiple case study	Literature, expert studies and case-studies	Explorative, theory development & prescriptive
Study C	Paper III		x	Case study survey	Cross-sectional survey, interviews	Quantitative survey analysis (descriptive statistics), content analysis

As mentioned earlier, the overarching philosophy of this research is based on a pragmatist view. This was because the focus was on finding practical solutions to real-world practices and the questions asked during the different studies. The research follows an explorative, inductive-reasoning approach (Given, 2008), drawing conclusions based on empirical evidence to create new knowledge or theory.

Two main types of research design were applied within this thesis: case study and literature review. The case study design, as proposed by Yin (Yin, 2014), was used in this thesis as it allowed closer contact with the organisations and people interviewed in the different studies in which the author participated. This led to the application of explanatory theories to shape the direction of the studies and their respective paper outcomes. Paper I used the multi-level perspective framework of sustainability transitions research and dynamic capabilities theory to understand stakeholder perspectives in sustainability transitions. Paper II used dynamic capabilities theory to understand the circular economy transition in digital supply chains. Paper III used resilience engineering theory to understand how industries may build resilience towards sustainability by implementing Industry 4.0 technologies.

A convergent mixed-methods design was then used. This was because both quantitative and qualitative data was collected to draw conclusions, based on empirical and theoretical evidence. In using this design, the intention was to combine the strengths and weaknesses of the two data-collection methods (Patton, 1990): Papers I, II and III used qualitative methods, such as interviews and expert panel studies to allow for in-depth, subjective interpretations in the studies. The quantitative methods used in Paper III, such as surveys and descriptive statistics, allowed for objective measurement and observation of sustainability implementation trends in manufacturing industries.

The details of the methods followed in each study may be found in the appended papers. The ways in which the different studies answer the research questions are described below:

RQ 1) What systemic challenges do manufacturing companies face when moving towards a digital and sustainability transition? (Studies A, B and Papers I, II)

The results from the first two studies carried out in this thesis (Studies A & B) helped answer RQ1. Study A (Paper I) used case study data from textile industries to identify the challenges they face in their sustainability transition process. The challenges identified aided understanding of the attitude of incumbent companies and their resistance to transformational change.

Study B (Paper II) was primarily explorative. It took a combined theoretical and empirical approach to understand and overcome the challenges that digital supply chains face in their circular economy transition process.

RQ 2) What enabling mechanisms can address these challenges and support the sustainability transition of production systems in the digital era? (Studies A, B, C and Papers I, II, III)

Empirical studies, in the form of expert interviews in Study B (Paper II) and quantitative surveys in Study C (Paper III), were conducted to understand the real-world conditions of I4.0 technology implementation and its feasibility in effecting successful sustainability transitions. Dynamic capabilities theory was explored in Studies A & B to overcome the specific systemic challenges identified and support green technology innovation (Paper I) and the use of I4.0 technology implementation (Paper II) in transitioning towards sustainability. Quantitative surveys and qualitative interviews were conducted in Study C to explore the potential of I4.0 technologies to build industrial resilience towards sustainability.

3.3 RESEARCH METHODS EMPLOYED

Based on their objectives, the three studies conducted in this research followed different methods in answering the RQs. The following sections briefly describe the data-collection methods and analytical and validation procedures used, details of which may be found in the appended papers.

3.3.1 Study A (Paper I): Empirical study

The purpose of Study A was to: evaluate whether a sustainable business case existed for a novel, water-free textile dyeing technology; understand the challenges that 'locked-in' textile industries face in implementing such technologies; and formulate a decision framework to help textile industries transition towards more sustainable practices. This study was conducted primarily to understand how radical transformations within niches may influence industries with highly structured operations (incumbents).

The study followed a qualitative approach and was carried out in two stages. In the first stage, primary data was collected from the industrial partner DyeCoo's facilities in the form of a study visit and a workshop held on its premises. These enabled the identification of stakeholders in the textile industry and their subjective values to innovation implementation. This was followed by primary data collection in the second stage which helped identify the barriers faced by textile industries regarding green technology implementation and radical sustainability transformation. The challenges identified were categorised during the data analysis phase using the PEST (political, economic, social and technological) analysis framework (Sammut-Bonnici and Galea, 2015) and answered RQ1.

Since the study identified the role of different players and the corresponding barriers to sustainability transition in the textile industry domain, a well-known framework was used. This was the multi-level perspective (MLP) approach which incorporates the multi-dimensionality complexities of sustainability transitions. A prescriptive decision framework was developed (see Figure 6) using dynamic capabilities theory to address the barriers to green technology implementation in textile industries, thus answering RQ2.

3.3.2 Study B (Paper II): Theoretical and empirical study

The aim of Study B was to contribute to theory by exploring how dynamic capabilities might be used to promote circular economy practices in supply chains. Hence, Paper II (which emerged from this study) had a two-fold purpose: (i) explorative – to uncover areas for theory development in the areas of dynamic capabilities, industrial symbiosis, circular economy and Industry 4.0; and (ii) collaborative theory-building – to identify dynamic capability variables in the areas of interest and the relationships between them.

The study had a multi-method qualitative case study design with data triangulation carried out for the data-collection process. Secondary data was collected from two case studies, alongside primary data from nine expert panel interviews and literature data. The rationale for choosing the two case studies for Study B was that they enabled convergence of the topics, alongside the common objective of overcoming collaborative challenges to digitalisation and implementing industrial symbiosis. Nine expert interviews were conducted, using questions derived using an inductive-abductive method consistent with the objectives of the study and literature. The theoretical model (developed from the literature and case studies) was tested with experts in the chosen domains. This validation helped refine the theoretical findings, provided validity in an industrial context (Platts, 1993) and developed the final dynamic capabilities model for promoting circular economy.

The data structuring methodology proposed by Gioia (Gioia et al., 2012) was used to demonstrate the connections between the emergent concepts from data and theory. First-order categories emerged from the interviewee quotes. The similarities and differences in these categories were then studied scrupulously, to understand the deeper structures and relationships within the derived data. This led to the more abstract second-order thematic level of coding. These codes were further combined into 'aggregate dimensions' or 'micro-foundations' – the subject of the study.

The study resulted in two main findings which may be found in Chapter 4, under Section 4.2.2. Hence, theoretical and empirical data was combined to understand challenges and demonstrate the use of dynamic capabilities theory in enabling a circular economy transition in I4.0. This answered RQs 1 and 2.

3.3.3 Study C (Paper III): Empirical study

Study C used a cross-sectional survey design (Mills et al., 2010), in which information was collected from a sample population of 78 projects within the Swedish Innovation Programme's Produktion2030. The purpose of the study was to quantitatively measure the extent to which Swedish manufacturing industries have implemented sustainability and I4.0 aspects in their operations. The data-collection methods used were quantitative surveys (primary method) and interviews. The study empirically investigated the trends of sustainability aspects, incorporated assessment methods and the extent to which I4.0 technologies were implemented to derive sustainability benefits (answering RQ2).

The I4.0 design principles and corresponding sustainability and circular economy benefits were mapped using literature data and the project case studies. Projects that had implemented I4.0 technologies to positively impact sustainability were contacted again and the managers interviewed to determine the validity and accuracy of the initial findings (Creswell, 2003). This also gave rise to the mapping of new relationships and insights for the implemented I4.0

technologies and the corresponding sustainability benefits gained. As described in Chapter 2, I4.0 technologies have the potential to build industrial resilience towards sustainability. Hence, an investigation was made of how far Swedish manufacturing industries have been able to develop resilient responses to sustainability challenges using I4.0 technologies, (also a contribution to RQ2).

4

"The future belongs to those who are able to manage uncertainty and innovate rapidly"

– Jag Srai

RESULTS

This chapter presents the results in relation to the two research questions of the thesis. The results stem from the three studies conducted during the research and the corresponding papers emerging from the studies (Papers I, II and III).

4.1 RQ1: SYSTEMIC CHALLENGES TO SUSTAINABILITY AND DIGITAL TRANSITION

One of the key steps in studying sustainability transitions is understanding the current operations and challenges that industries face in the transition process. Studies A and B helped identify some of these systemic challenges.

4.1.1 Key challenges to sustainability transition

Study A was undertaken to identify the critical barriers that textile industries face in adopting green technologies and achieving large-scale radical transformations towards sustainability. These barriers were identified by studying the complex and dynamic interactions of the different stakeholders and levels of influence, using a well-known sustainability transition framework called the multilevel perspective (MLP) framework.

The barriers identified in the study were categorised under different emergent themes and represented using a PEST (political, economic, social and technological) model ((Sammut-Bonnici and Galea, 2015). PEST modelling is typically used to manage risks or factors that may have drastic impacts within organisations. The model helped categorise the challenges and depict them using a nested view of the triple bottom line approach.

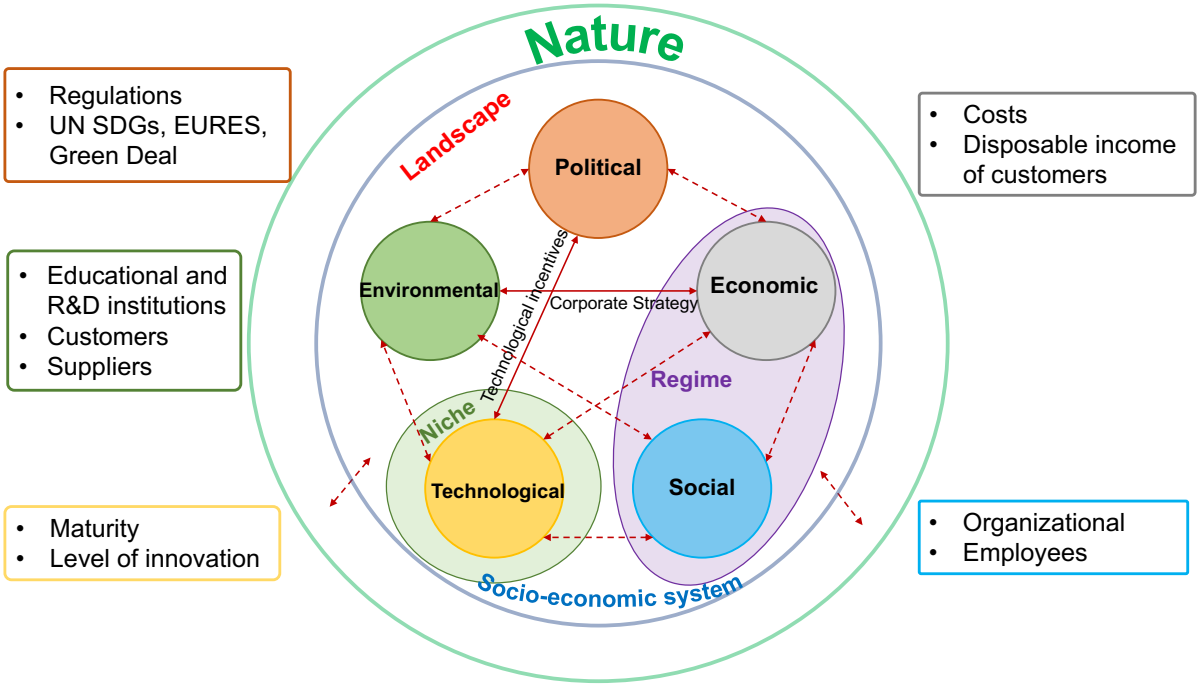

Figure 6. Challenges to green technology implementation in textile industries (from Paper I).

The challenges derived from the primary data collected in this study (details of the data-collection method may be found in Paper I) were categorised under the following factors: Political (regulations and global policies); Environmental (academic and research institutions, customers and suppliers); Social (stakeholders within the organisation alongside their knowledge, skills and strategies); Technological (innovation and corresponding maturity levels); and Economic (related internal costs and disposable incomes of customers). The challenges under 'Political' and 'Environmental' were considered to be part of an external 'landscape' influencing or pressuring existing socio-economic and socio-technical organisations (dominant regimes) to transition towards sustainability. Challenges under the 'Social' and 'Economic' categories were considered to be part of regime structures or firms

with highly structured operations. The innovations or technological developments occurring in niches were categorised as part of the 'Technological' challenges.

4.1.2 Key challenges to combined sustainability and digital transition

Study B was carried out to analyse collaborative challenges in manufacturing supply chains to circular economy and digital transition efforts. Data was collected from two supply chains (secondary data) and expert interviews. Details of the data-collection process may be found in Paper II. Three main challenge themes emerged from the data analysis: organisational, external and data/information/knowledge. These are shown in Table 3.

Table 3. Identified collaboration challenges to CE and digitalisation efforts (from Paper II).

Study	**Challenge categories**		
	Organisational	**External**	**Data/information/knowledge**
A: SME supply chain	- Skills of technical sales personnel - Traceability of purchased stocks - Communication - Cross-functional collaboration amongst departments leading to sub-optimised design processes of new and existing products - Lack of digital tools in the development phase of a new product	- Order handling: visibility of order status (organisational and with partners of value chain) - Standardised information systems among supply chain partners - Different routines and systems in place for handling data and information exchange	- Data availability - Visualisation of data - Connectivity - Some data is not digitalized - Varying quality of MRP systems to manage document handling - Vague email requests for new orders - Underutilisation of ERP systems
B: Industrial Symbiosis implementation inquiry	- Communication, coordination and management (planning) - Leadership support - Cultural mindset - Trust - Capacity and capability - Business-as-usual - Missed sustainable value opportunities - Lack of skilled technologists and IT specialists - Identification of value embedded in the waste streams - Identification of synergistic linkage opportunities and implementation requirements	- Geographical / spatial factors - Regulations at firm and network levels - Regulations at government, regional, local, city authority levels - Policies to incentivise - Complexity, continuity and mismatches in the capacities/capabilities among different partners - Weak and unstable demand factors	- Poor quality of data on waste - Different volumes and types of data due to different locations makes data collection and processing economically unfeasible. - Lack of information - Materials diversity - Material quality at unpredictable flow rate - Classification of materials as waste instead of useable by-product - Data collection required time input by firms
C: Expert interviews	- Lack of understanding the CE concept - Lack of knowledge of applying the right environmental assessment method - Difficulty in intra-organisational collaboration	- CE is not understood in the same way by the different partners in the supply chain - Supply chain and logistic system design challenges - Existing institutional conditions - Lack of funding mechanisms - Varying sustainability intent of the supply chain partners	- Lack of cross-functional horizontal and vertical integration of competencies and communication

The challenges categorised as 'organisational' were mainly internal to the focal firm(s) in the supply chain. Common organisational challenges were: lack of skills and leadership; lack of understanding of strategic environmental goals and meaning of circular economy; and lack of identification of value opportunities and communication within the firm.

External challenges included those challenges related to supply chain partners as well as those outside the focal firms. That is, apart from the external challenges identified regarding supply chain partners (mismatch in organisational routines, skills, technology readiness levels and how CE concepts are understood and implemented), other external challenges identified were: changing demand factors; lack of funding mechanisms; and varying regulations based on geographical conditions.

Lack of comprehensive data availability and quality among the different supply chain partners was identified as another key challenge to transition efforts. Varying geographical locations, infrastructure and lack of uniform planning systems played a vital role in poor data quality and the emergence of different types of data.

4.1.3 Summary of challenges found in Studies A & B

Studies A and B contributed to a holistic understanding of the systemic challenges faced by manufacturing industries that are moving towards a sustainable and digital transition, thus answering RQ1. Study A (Paper I) broadly helped identify the sustainability challenges of textile industries and Study B (Paper II) with its two case studies and expert interviews, helped in understanding the challenges to circular economy and digital implementations in supply chains. Despite many global initiatives to drive industries towards more sustainable forms of production, the challenges identified from the two studies showed that manufacturing industries still face holistic barriers to their sustainability and digital implementation efforts.

Three common themes of challenges were identified by combining the results from studies A and B: internal, external and technological. Internal challenges were further found to have organisational (structures, routines, strategies, cultural mindset), financial, skills/capabilities and communication factors. External challenges were those found in the supply chain partners plus those outside the firms (funding mechanisms, regulations, global policies, influence of customers and collaboration with stakeholders). Technological challenges included varying innovation or digital maturity levels, different types and quality of data and lack of information on waste/value capture opportunities in firms and their supply chain partners.

Varying maturity levels of sustainability and digitalisation implementation, alongside a mismatched clarity of understanding of sustainability, circular economy and I4.0 concepts were some of the fundamental challenges identified across the three challenge themes.

4.2 RQ2: ENABLING MECHANISMS FOR SUSTAINABILITY TRANSITION

Although manufacturing industries have tried to incorporate sustainability aspects into their business models and operational practices, challenges to, and uncertainties in this incorporation still remain. Not all adopters can harvest the benefits anticipated in the literature. The systemic challenges that manufacturing industries face were addressed in the previous section, answering RQ1. The development and implementation of certain enablers were then studied; ones which could help overcome the challenges, enabling the sustainability transition of manufacturing industries and helping answer RQ2. As described before, three specific enablers were chosen to support the sustainability transition of manufacturing companies in the digital era: Industry 4.0 technologies, dynamic capabilities and resilience engineering. These are described below.

4.2.1 Industry 4.0 technologies for sustainable manufacturing

Theoretical and empirical studies were undertaken through Studies B and C (Papers II and III). These were done to understand the various available I4.0 technologies which facilitate sustainable production practices and the extent to which they are implemented.

A literature review conducted in Study B (Table 4) indicated that big data analytics may improve data capture and monitoring. It thus addressed the challenges related to the potential value that might be captured from waste streams in a circular economy context. The use of IoT may enable increased transparency and availability of information on resource consumption and thus improve productivity, production flexibility and resource efficiency. IoT also allows for improved customer profiling, better understanding of their needs and improved communication with customers. Cloud manufacturing and virtual platforms make data easily accessible when required, thus creating a shared network of resources and capabilities. This enables the building of long-term relationships, increasing competitiveness and creating sustainable value among supply chain partners. 3D virtual simulations of production and supply chain operations may help optimise production planning and resource flows and prepare for uncertain market fluctuations. Virtual development (VD) tools such as augmented reality (AR) and virtual reality (VR) allow high-speed prototyping. This helps reduce costs, machine downtime and waste due to the increased availability of real-time information.

Table 4. Core technologies that facilitate sustainable (especially CE) practices (Literature review from Paper II).

I4.0 Technologies	Potential	Reference
Big data approaches	Addresses the barrier created by a lack of robust data in relation to waste streams	(Song et al., 2017)
Internet of Things (IoT)	- Data acquired from electronic devices and data exchange can control/monitor the processes efficiently to support IS - Using an IoT platform and management system, the economic, environmental and efficiency performance in complex production systems may be simultaneously assessed	(Atzori et al., 2010, Baptista et al., 2018, Hu et al., 2016, Kang et al., 2016, Xu et al., 2014, Zhang et al., 2017, Ferrera et al., 2017)
Cloud manufacturing	- Virtual portals create a shared network of manufacturing resources and capabilities offered as services - Handle high-volume data with improved accessibility and standards at low setup and operating costs. Self-learning capability with real-time information flow, remote monitoring, enhanced continuous communication	(Yu et al., 2015, Zhang et al., 2010, Gupta et al., 2019)
Cyber-physical systems (CPS)	Enables automation, monitoring and control of processes and objects in real time via controllers and sensor systems	(Wang et al., 2015, Yu et al., 2015)
Simulations	Helps increase confidence in synergy efforts as simulations of economic implications may reflect how prices fluctuate, thus making them attractive to firms	(Karner et al., 2017)

However, challenges to I4.0 implementation for sustainability still exist, as research in the area is still evolving. There are various uncertainties regarding the sustainability benefits of the technology implementation and long-term sustainability impacts. Hence, Study C was conducted to empirically understand the extent to which these opportunities have been implemented to obtain sustainability benefits in Swedish manufacturing.

From the cross-sectional survey carried out in the study, it was seen that sensors, virtual development tools and artificial intelligence/machine learning technologies were the most-implemented I4.0 technologies in the case companies (Figure 7).

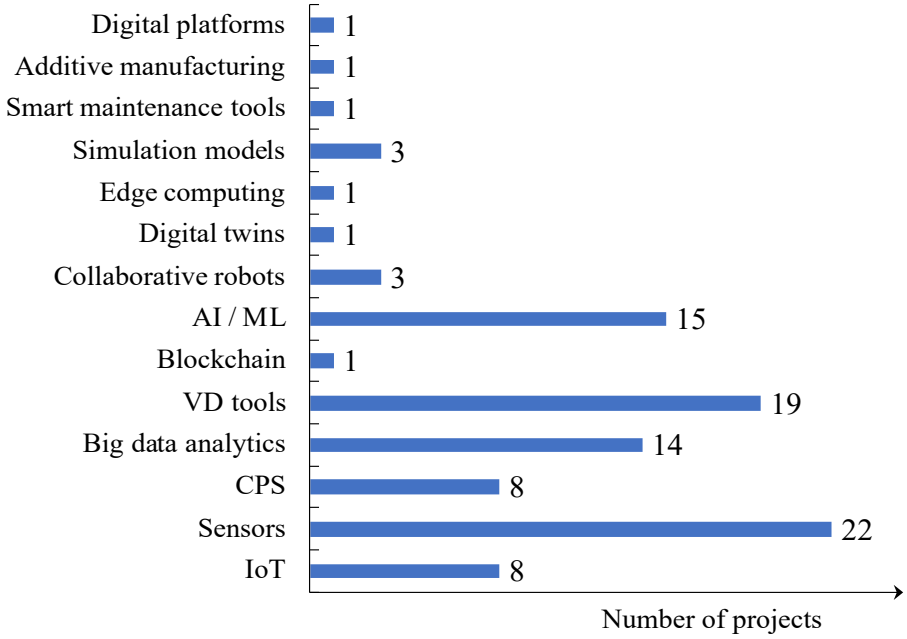

Figure 7. I4.0 technologies implemented for sustainability (From Paper III).

The survey findings were also compared with data from the literature (Table 5) for the different I4.0 technologies implemented in the study, I4.0 opportunities and the corresponding sustainability and CE benefits. The 'o' indicates data from the surveys and the 'x' signifies data from the literature. Additional details of Study C may be found in Paper III.

Of the 78 projects surveyed in this study, 65% were seen to have implemented I4.0 technologies to gain sustainability benefits. This shows an increasing trend of I4.0 technologies as an enabler of sustainable manufacturing in Sweden. Also, 35% of the projects implemented CE principles (prolonging loops, prioritising the waste hierarchy, remanufacturing and component reuse at product, process and value-chain levels).

Overall, the sustainability and CE benefits derived from I4.0 implementation involved, increased production efficiency. This, in turn, increased resource efficiency, enabled zero-defect production, reduced machine set-up times and costs, improved working conditions and led to shorter product development lead times.

Some of the specific I4.0 opportunities for deriving sustainability benefits were: use of AI/ML and big data analytics to extend the longevity of machines and products. This gave rise to lower energy consumption, waste and emissions. Simulation models helped reduce product lead times. This resulted in lower resource consumption and improved product quality. Additive manufacturing was used as a circular economy strategy, thus reducing the need to recycle scrap. VD tools helped in better conveying information and assigning the correct workload to operators. This resulted in a reduction in errors and cost to the company.

Table 5. Industry 4.0 opportunities and sustainability benefits (From Paper III).

I4.0 technologies implemented	Opportunities of Industry 4.0					Sustainability and circular economy benefits				
	Production flexibility	Process efficiency	Prototyping speed	Machine set-up	Customer relations	Resource efficiency	Working conditions	Extended lifetimes	Production waste	CE practices
Digital platforms			o			o			o	o
Additive manufacturing		o	x	x	x	o			x, o	o
Smart maintenance						x, o		o	o	o
Simulation models		o	x	x		o				o
Edge computing						o				
Digital twins			x	x					o	o
Collaborative robots	x	o	o	x		o	o	o	o	o
AI/ML		o		x, o	o	o	o	o	o	x, o
Blockchain		o			x	x, o			x, o	x, o
VD tools	x, o	o	x	x	x	x, o	o	o	x, o	o
Big data analytics	x	o		o	x, o	x, o	o	o	x, o	o
CPS	x, o	x, o		o	o	x, o	o	x, o	x, o	x, o
IoT	x, o	o		x, o	x	x, o	o	x	x, o	x, o

Another overall benefit of the I4.0 technology implementation was the increased availability of data and information. This gave rise to increased visibility in production logistics, increased information on customer demands and improved decision-making on sustainability at different levels of the organisation.

4.2.2 Incorporating dynamic capabilities to improve sustainability transition efforts

4.2.2.1 Identification of dynamic capability constructs

Teece (Teece and Pisano, 1994) explained that dynamic capabilities are unique to firms, determining how they build and reconfigure their internal and external competences to deal with changing circumstances whilst helping them stay competitive. In response to the specific challenges identified in Study A (Figure 6), a prescriptive, stepwise decision framework was formulated (Figure 8) to help textile industries implement green innovations and enable the transition towards more sustainable practices. This framework was based on the dynamic capabilities approach, in which organisations should 'sense' the different challenges, 'adopt' best-practices to overcome specific challenges and thus 'transform' their operational processes to derive long-term sustainability value.

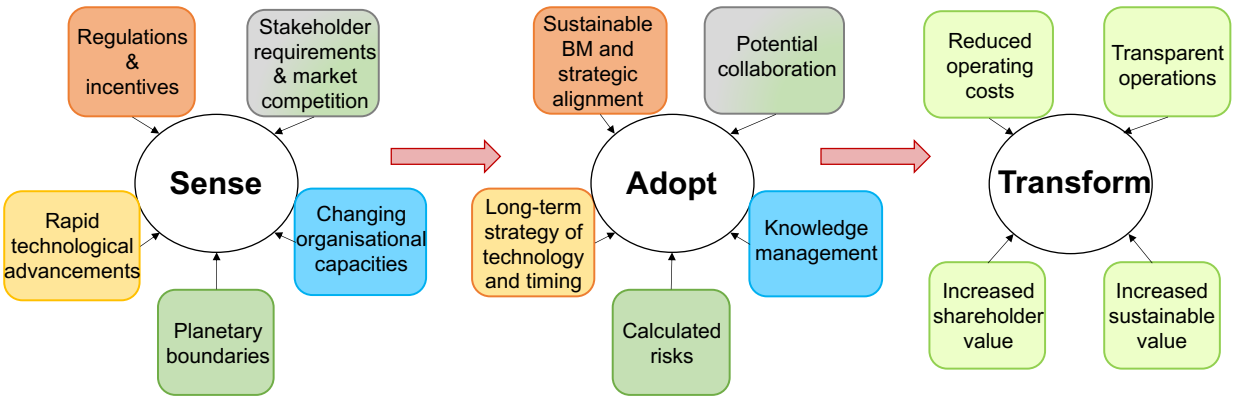

Figure 8. Decision framework for sustainability transition of textile industries (From Paper I).

The specific factors identified which underpin the 'adopt' dynamic capability were: develop

sustainable business models and strategic alignment; partake in collaborative activities with partners; incorporate knowledge management as part of horizontal integration activities; take calculated risks; and invest in long-term strategies of technology implementation at the right time. The benefits that might be obtained by following this transition pathway are depicted in light green, to the far right of Figure 8.

The literature suggests that the development and incorporation of dynamic capabilities may also help overcome circular economy implementation challenges in organisations (Ritzén and Sandström, 2017, Geissdoerfer et al., 2017). Hence, Study B used the dynamic capabilities theory to promote circular economy practices and improve sustainability performance in digital supply chains. The idea was to use the theory to bring together two relatively well-established concepts (such as Industry 4.0 and circular economy) in a manufacturing supply chain context. A detailed analysis of the literature was conducted, in which different I4.0 technologies (Table 4) and capabilities (Table 6) were identified which may support the transition of supply chains towards circular economy practices.

Table 6. Capabilities to enable circular economy transition (From Paper II).

Areas	Capabilities	Reference
Organisational factors	Internal organisation	(Kabongo and Boiral, 2017, Lai et al., 2015, Prieto‐Sandoval et al., 2019, Schuh et al., 2016)
	Interaction with value network	(Schuh et al., 2016, Watson et al., 2018, Baas, 2008)
	Operational	(Baas, 2008, Watson et al., 2018)
	Cultural	(Machado et al., 2019, Schuh et al., 2016, Eamonn, 2015)
Resources	Physical resources	(Dangelico et al., 2017, Prieto‐Sandoval et al., 2019)
	Human resources	(Deloitte and The Manufacturing Institute, 2018, Schuh et al., 2016, World Manufacturing Forum, 2019)
Technology	Digital competencies	(Schuh et al., 2016)
	Information processing	(Schuh et al., 2016)
	Information system integration	(Schuh et al., 2016)
	Innovation	(Gupta et al., 2019, Baas, 2008, Kabongo and Boiral, 2017, Storer and Hyland, 2009)
Knowledge factors	Learning	(Beske et al., 2014, Kabongo and Boiral, 2017, Prieto‐Sandoval et al., 2019, Schuh et al., 2016)
	Structured communication	(Schuh et al., 2016)
External factors	Regulations	(Machado et al., 2017, Baas, 2008)
	Networking	(Song et al., 2017, Kabongo and Boiral, 2017)

The Acatech Industrie 4.0 maturity index model (developed to support industries as they digitally transform (Schuh et al., 2016)) was used to identify the initial capabilities in Study B (Paper II) required for a CE transition. This model was chosen because its capability dimensions might help overcome the collaborative challenges identified in the study and help create decision support by improving data and knowledge exchange. From the literature review, capabilities which might support circular economy practices were identified in five main areas: organisational factors, resources, technology, knowledge and external factors.

Secondary data from two case studies was then used to understand the collaborative challenges to a digital and circular economy transition within supply chains. Finally, nine expert interviews were conducted to enrich and support the theoretical capability findings. Two main results emerged from the study: (1) a dynamic capabilities model which described the capabilities required to transition to circular economy, particularly industrial symbiosis in I4.0 (Figure 9) and (2) the underlying relationships and dependencies between the derived capabilities (Figure 10).

The thematised first and second-order coding (in Figure 9) resulting from the expert interviews, revealed five microfoundations of dynamic capabilities, namely: communication, organisation, resources, collaboration and technology. These were categorised under the three dynamic capabilities of 'sense', 'seize' and 'transform'. Additional details of how the data was coded may be found in Paper II (contribution from Study B). The categorisation of the various microfoundations under the dynamic capabilities are described in the following sections.

Sense

Data, information and knowledge were categorised under the microfoundation 'communication'. This was then categorised under the dynamic capability 'sense'. One of the key findings under this capability was how the circular economy concept is understood and implemented among the different supply chain partners. Without a clearly defined vision, it will be difficult for industries to embark on a transition journey. Once a standardised definition is agreed upon, the knowledge and strategy will then need to be communicated across different levels (vertical alignment within the organisation and horizontal across the various partners in the value network) and a compromise needs to be arrived at, among partners. Sense acts as a foundational capability because once the right factors are understood and implemented under this capability, 'seizing' and 'transforming' can become standard capabilities. Companies will be able to monitor their circular economy transition by comparing with external standards but only if the CE concept is well-established and understood in their internal operations. Systematised data-sharing and understanding the different needs of the value-chain partners is another important aspect of this capability.

Seize

'Organisational' and 'resource' microfoundations play a key role under the 'seize' capability and factors such as manufacturing strategy, financial, value capture, leadership, company culture, social aspects and physical resources were categorised under them, as shown in . Transitioning to CE generally occurs in the conceptualisation phase. However, when it comes to the specific achievement of industrial symbiosis, the challenge lies in the implementation or seizing phase. So, important microfoundations that needed to be considered under the 'seize' capability were categorised accordingly.

Trust was seen as an important factor that can help build collaboration and communication between value-chain partners and, in turn, help seize new business opportunities. In terms of increasing sustainable value capture, building symbiotic infrastructures and business models might bring many new opportunities. Another important factor was the cultivation of an organisational mindset that went beyond conformity to environmental regulations, alongside the support of stakeholders at different levels of the company. Investment and the creation of suitable financial structures were important in bringing about change within the organisation, coupled with a strong focus on allocating the right skills and physical resources to different operations which may not directly be at the core of the business.

Transform

The microfoundations 'collaboration' and 'technology' were categorised under the 'transform' dynamic capability. Without the recognition of a technology implementation strategy, collaboration with partners and a commitment to change, large-scale circular economy benefits will be largely unknown, and the transition will not take place. Additional details of these results may be found in Paper III.

The sustainability benefits arising from I4.0 opportunities seen in the literature were also expressed during the expert interviews. Participants shared their view of technologies such as 3D printing, which has been known to reduce production waste, create profits due to reductions in errors and have the ability to optimise productivity. However, the quality, behaviour and lifetime of the final products in regard to CE are still largely unknown. Moreover, although industries are heading in the right direction regarding technology implementation to enable sustainability benefits, some may be unaware of the full picture or the benefits of such an implementation. This is when a joint effort by researchers and industries to operationalise new, convergent topics may benefit the transition process.

4.2.2.2 Relationships between the different dynamic capabilities

The second finding from Study B was the emergence of relationships between the circular transition capabilities which had been derived (Figure 10). The microfoundation 'leadership' was found to be a key foundational contributor to the other capabilities. Without leadership support, the development of other capabilities may not be possible. Similarly, a sound manufacturing strategy will enable digital implementation, the cultivation of an adaptable strategic mindset and help in reconfiguring business models. These were then seen to impact cross-functional collaborations and connections with supply chain partners. Additional relationships and their details may be found in Paper II.

4.2.2.3 Summary of the dynamic capabilities

Summarising the capabilities identified from Studies A and B (Papers I and II), industries will need to adopt 'sense', 'seize' and 'transform' dynamic capabilities to move successfully towards sustainability transition practices. Specifically, the development and implementation of the five microfoundations of dynamic capabilities (identified in Paper II) will generate unique competitive advantage and improve sustainability performance in the firms and their value-chain partners. Further, the dynamic capabilities identified were complementary to those found in the literature; the extent to which they are implemented depends on firms' requirements and maturity levels.

First order codes *(derived from participant quotes)*	Second order codes *(categories)*	Aggregate dimensions *(microfoundations)*
Sense		
• Systematise data-sharing for better logistics of output resource handling (E) • Source local materials to have data inflow at different stages of manufacturing (D) • Understand data-sharing needs of the different partners in the value chain (H) • Integrate RAMI 4.0 for structured data communication (I)	**Data**	**Communication**
• Educate workers on circular economy practices on the shop floor (C) • Strive for education and knowledge sharing to tackle common problems in the value network (E)	**Information**	
• Gather information at the design phase to make more sustainable products (C) • Standardise definition of circular economy (A, B, C, D, E, F, H)	**Knowledge**	
Seize		
• Develop new manufacturing processes, procurement of materials and inbound logistics (D) • Implement agile manufacturing to accommodate different types of products for CE (C) • Build new supply chain structures, logistics systems and logistics structures (D) • Develop environmental-orientated priorities rather than only technology-oriented (from I4.0) (G)	**Manufacturing strategy**	**Organisation**
• Create suitable financing interests, instruments or structures (F) • Allocate cost of the wastes generated to the right department within the company (B) • Investment in R&D for alternative raw material processing techniques (D)	**Financial**	
• Reconfigure business models that combine physical asset and service as a product (E) • Explore new "inter-organisational" transparent and equitable business models (F)	**Value capture**	
• Support from top-level management (C) • Internal motivation and commitment towards environmental improvement (G)	**Leadership**	
• Cultivate an adaptable strategic mindset (F) • Willingness to change within different hierarchical levels (B)	**Company culture**	
• Develop the right skills for enabling the right material flows and maintain eco-efficiency (E) • Incorporate attention to human rights, employee well-being and inclusivity (D)	**Social aspects**	**Resources**
• Assign resources to operations that are not core business (E)	**Physical resources**	
Transform		
• Change in mentality beyond the individual companies, i.e., in the different companies of the value network (D)	**Supply chain culture**	**Collaboration**
• Support cross-functional collaboration within the company (H) • Develop common infrastructural solutions by collaborating with industries in the network (E) • Identify customer needs for the purpose of the product (C) • Create end-to-end connection with suppliers & waste entrepreneurs for combined decision making (B)	**Internal and external collaboration**	
• Create good relationships and make business opportunities visible (F) • Understand allocation of responsibilities between manufacturers, suppliers and users (C) • Involve local partners in circular economy activities (C)	**Stakeholder involvement**	
• Use the potential of I4.0 to trace raw materials at its source (D) • Understand the requirements of data derived from technologies & how to present results (H) • Use simulation and maintenance to reduce lead time and increase lifetime of product (I)	**Digital**	**Technology**
• Innovate at different levels: business model, process and human interactions (F) • Develop preventive and condition-based maintenance (B) • Develop indicators to measure share of reused/recycled products in the market along with extending its utility value (C)	**Innovative tools**	

Figure 9. Dynamic capabilities necessary for a circular economy transition in digital supply chains (From Paper II).

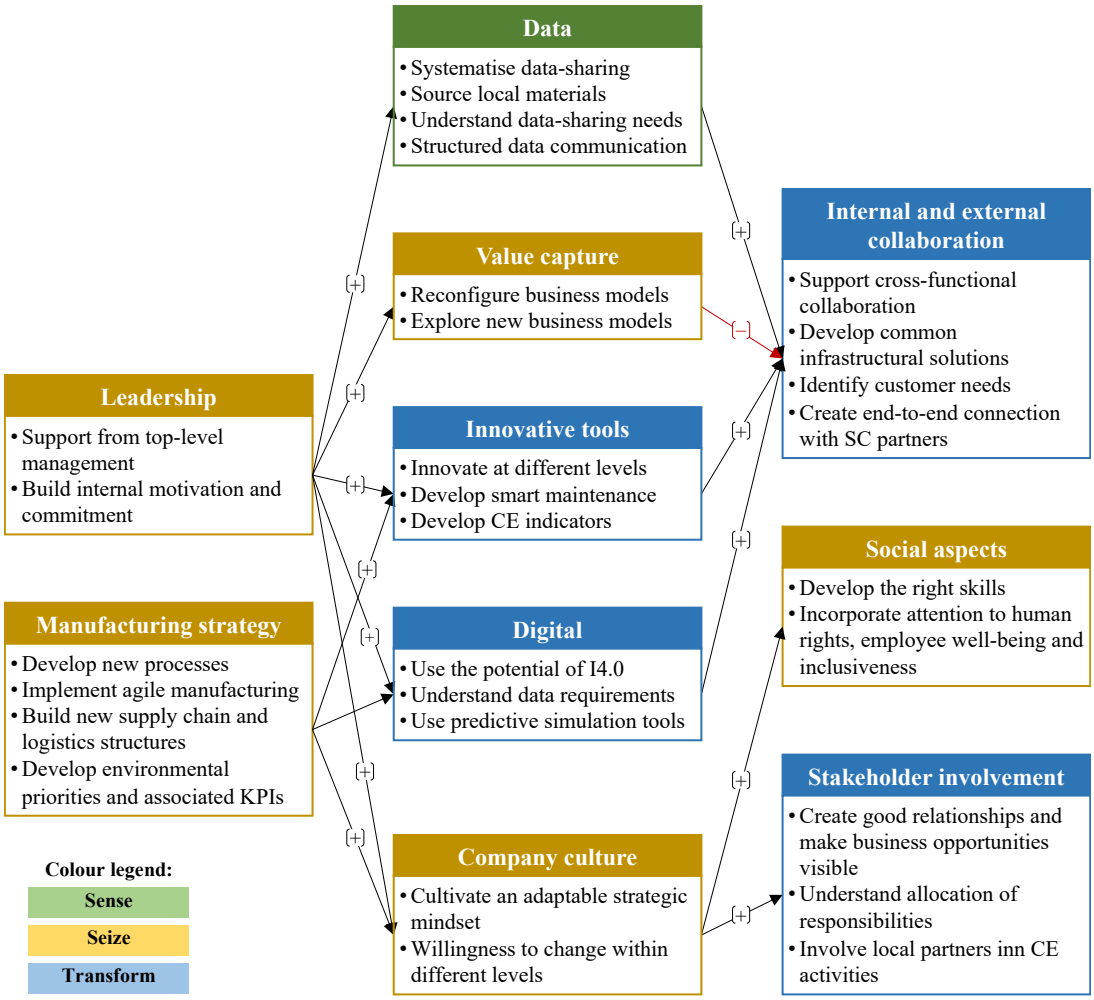

Figure 10. Relationships between the capabilities (From Paper II).

4.2.3 Building industrial resilience to gain sustainability benefits in Industry 4.0

Paper III (outcomes of Study C) describes how industries may build resilience towards sustainability using the potential of I4.0 technologies. As previously defined, resilience strategies can prepare an organisation to respond to unplanned events, avoiding or minimising their impact. Ultimately, managing resilience capabilities in industries and their supply chain partners may help them achieve sustainability objectives (Fiksel, 2017). Five dynamic phases from the literature were then applied to the context of I4.0 (Study C, Paper III). These are shown in Figure 11.

Five key industrial factors were identified from I4.0 opportunities to build resilience towards sustainability benefits. These are depicted in Figure 12. An increase was observed in operational efficiency relating to resources, time and energy. This was due to the implementation of several I4.0 technologies, such as additive manufacturing, simulation models, collaborative robots and so on (see Table 5). The literature on resilience supports the argument that increasing operational efficiency may help build resilience to sustainability challenges (World Economic Forum, 2020). I4.0 technology implementation also allowed new agile forms of data-collection processes. This resulted in reduced production waste and scrap. The literature describes how incorporating agility is a form of resilience-building

towards gaining sustainability benefits (Ivanov, 2020).

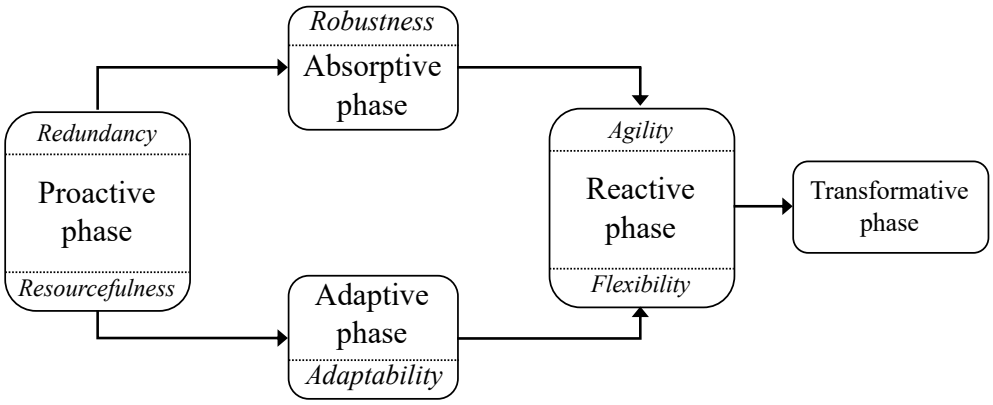

Figure 11. Dynamic phases for a resilience response towards sustainability (Adapted and modified from (Amadi-Echendu and Thopil, 2020, Conz and Magnani, 2020), Paper III).

Due to the increased availability of data and information from the I4.0 technology implementation, there was an increase in transparency and visibility of production logistics. This resulted in increased resource efficiency, increased sustainable value, improved customer relations due to an understanding of demands, less waste and shorter lead times. The literature supports the idea that increased transparency and visibility of processes may increase the resilience of organisations (Amjad et al., 2020).

The implementation of simulation models was used to assess the potential of circular business models such as product-service-systems, thus leading to shorter lead times, lower resource consumption and improved product quality. Business model innovation is recognised as a critical success factor in building resilience and increasing sustainability (Carayannis et al., 2014). Further, the implementation of IoT and CPS allows for better machine set-ups and reduced machine downtimes, thus allowing a seamless adaptation to changing circumstances (in effect the 'flexibility' of the operations). Flexibility is yet another important characteristic of building industrial resilience (Bhamra et al., 2011, Santos Bernardes and Hanna, 2009).

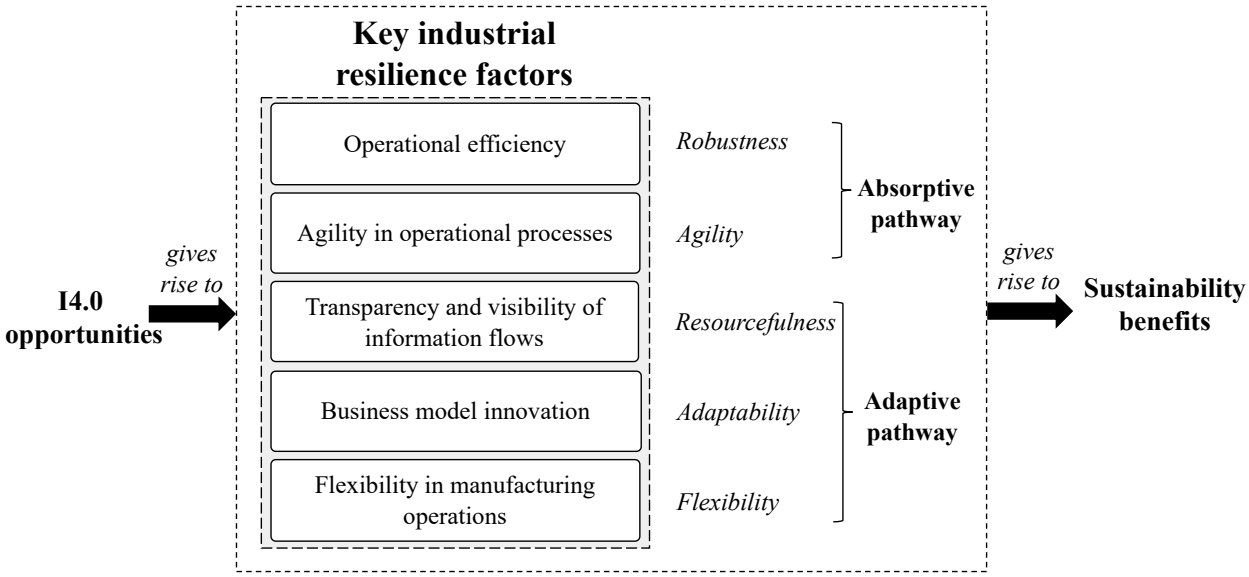

Figure 12. Industrial resilience factors from I4.0 opportunities (From Paper III).

5

"The good thing about science is that it's true whether or not you believe in it"

– Neil deGrasse Tyson

DISCUSSION

This chapter discusses the results in relation to the research questions and previous work, plus how it contributes to a systemic understanding of sustainability transitions. It also describes the theoretical and practical contributions of the research and provides brief notes on future work.

5.1 OVERVIEW

This chapter discusses the research according to the following five sections:

- The thesis in relation to previous work.
- The extent to which the results contribute to answering the research questions.
- The extent to which the results contribute towards building scientific knowledge (theoretical contribution) and can support industrial practitioners (practical contribution) to transition towards sustainability.
- Quality of the research.
- Limitations and future work.

5.2 RELATING THE THESIS TO PREVIOUS WORK

I4.0 opportunities, such as production flexibility, productivity, operational efficiency, data capture and monitoring and process transparency (Büchi et al., 2020, Carvalho et al., 2018, Hermann et al., 2015) have been known to provide sustainability and CE benefits. The results from the thesis revealed that 65% of the surveyed manufacturing companies (Paper III) implemented I4.0 technologies to derive sustainability/CE benefits.

In addition, some of the sustainability benefits seen from literature include improved resource consumption, long-term relationships with customers and suppliers, cost and waste reductions, improved working conditions (Bonilla et al., 2018, Müller et al., 2018, Stock and Seliger, 2016) and implementation of CE practices (Benedict et al., 2018, Ellen MacArthur Foundation, 2016, Nascimento et al., 2019). The I4.0 technologies implemented in the present thesis and the corresponding sustainability benefits derived were: use of AI/ML to enable zero-defect production and extend product/machine longevity; use of VD tools to better present information to workers and help reduce machine set-up costs and errors; combined use of VD tools with collaborative robots to simulate and investigate alternate forms of production, thus lowering costs; use of collaborative robots to give rise to a safe work environment and allow efficient cooperation between humans and robots (which, in turn, gave rise to resource-efficient operations). Additional findings from the literature and empirical studies may be found in Section 4.2.1, as detailed in appended Papers II and III.

According to Teece (Teece, 2007), microfoundations of dynamic capabilities provide unique competitive opportunities to firms so that they may address changing circumstances. Previous research has also explored the sustainability perspective of incorporating dynamic capabilities in industries (Dangelico et al., 2017, Machado et al., 2017). Against this background, the present work revealed that dynamic capabilities may support industrial sustainability transitions through: (i) a prescriptive decision framework (Paper I), in which manufacturing companies should 'sense' customer requirements and foresee potential environmental impact (instead of the current defensive and reactive approaches), 'adopt' proactive green innovation strategies and 'transform' into sustainable value-creating firms; (ii) five microfoundations of dynamic capabilities (Paper II), based on organisational and technological aspects. These capabilities were also found to be deeply interconnected and interdependent.

The literature states that the above capabilities may also promote sustainable competitive advantage in industries (Eikelenboom and de Jong, 2019, Khan et al., 2020, Prieto-Sandoval et al., 2019) and that I4.0 technologies may provide opportunities to develop them (Gunther Schuh, 2020, Felsberger et al., 2020, Garbellano and Da Veiga, 2019, Gupta et al., 2020). Moreover, Teece (Teece, 2007) explicated that a sound management strategy plays a crucial

role in improving sustainability performance and collaborative activities with external partners in a value chain. From the interactions between the microfoundations found in Study B (Paper II), it was observed that support from top-level management and leadership abilities formed the basic foundation for developing other dynamic capabilities to promote CE in I4.0. The technological microfoundation was described as a key, transformative dynamic capability, if industries want to build considerable sustainable competitive advantage.

Resilience is another concept that has been considered a success factor in gaining a sustainability advantage in industries and supply chains (Gunasekaran et al., 2011, Rajesh, 2019). Recent studies have explored the potential of I4.0 to further enhance the sustainability and competitiveness of operations through the development of resilience (Amadi-Echendu and Thopil, 2020, Amjad et al., 2020, Kumar et al., 2020). Although this field is emerging, it was deemed to be worth exploring, considering the convergence of topics in this thesis. Hence, Study C (Paper III) explored how the sustainability of industries may be increased by building resilience by implementing I4.0 technologies. Details of the study may be found in Section 4.2.3 and appended Paper III.

5.3 CONTRIBUTION TO RESEARCH QUESTIONS

The aim of the thesis was to identify systemic problems or barriers to sustainability within existing production systems (RQ1) and investigate opportunities to fix or improve them, thus effecting system change (RQ2). This section describes the contribution of the results to the two research questions.

RQ 1) What systemic challenges do manufacturing companies face when moving towards a digital and sustainability transition?

The literature describes the development of sustainability performance management tools, metrics, capabilities/maturity models and transition frameworks. Yet, there remain several challenges to implementing sustainability in production operations. And although manufacturing industries have progressed in leaps and bounds over the last decade, in terms of sustainability awareness, there is no holistic view of the various implementation challenges and how they affect sustainability transitions in industries. Three main categories or themes of challenges emerged from the first two studies (Studies A and B) carried out in the research: internal, external and technological. These were despite the different geographical locations of the manufacturing companies/supply chains in the studies, their size and capabilities and external pressures.

Internal challenges were primarily organisational. This is not surprising as highly structured regimes are less willing to change their strategies and cultural mindsets. External challenges were seen in terms of a mismatch between the internal challenges of the value-chain partners and the focal company, as well as those in the landscape environment, such as funding, regulations and customer demands. From the empirical results of the present research and in the literature, it was found that data was at the core of technological challenges. The type, quantity and quality of data within and outside the focal company were seen to affect not only sustainability implementation efforts but also played a vital role in collaborating with value-chain partners. Overall, different maturity levels, in terms of sustainability and digital technology implementation, alongside a mismatch in understanding the concepts of sustainability, circular economy and Industry 4.0 within a company (and across its value-chain partners) were common underlying challenges upon which the other challenges emerged.

RQ 2) What enabling mechanisms can address these challenges and support the sustainability transition of production systems in the digital era?

Influenced by the literature and the UN's Green Deal, three enablers were chosen to deal specifically with the challenges identified in the thesis and support the sustainability transition of manufacturing industries: enabling technologies of Industry 4.0, dynamic capabilities and resilience engineering.

Several opportunities from I4.0 have previously been studied to promote sustainable practices. However, there are few empirical studies which understand the extent of the technological implementation and the potential sustainability benefits that might be derived. From the empirical and theoretical studies conducted in this thesis, it was observed that, apart from I4.0 technologies such as CPS, IoT, simulations, big data analytics and additive manufacturing (which can improve visibility and availability of data, resource efficiency and waste reduction in production processes), three technologies are being widely implemented in Swedish manufacturing to derive circular and sustainability benefits. These are: artificial intelligence/machine learning, virtual development tools, such as augmented reality (AR) and virtual reality (VR) and the use of sensors. These were specifically seen to improve the availability of real-time information and improve productivity, thus creating better working conditions, lowering resource consumption and waste, reducing costs and extending machine and product longevity.

As much as I4.0 technologies may positively influence sustainability outcomes, sustainability transitions will only succeed if the stakeholders adopting them have the right capabilities, culture and priorities in their own strategic agendas. Following this thinking, five closely-linked microfoundations of dynamic capabilities (communication, organisation, resources, collaboration and technology) were identified which may help industries and their value-chain partners in their sustainability transition processes. However, it is important to remember that the incorporation of these capabilities will differ between companies, according to their leadership abilities, maturity levels and requirements. Nevertheless, integrating dynamic capabilities may enable industries to identify future sustainability value-chain opportunities, thus improving their competitive advantage and overall sustainability performance.

The potential of I4.0 technologies for building industrial resilience towards achieving sustainability objectives was evaluated empirically in the thesis. The results showed that industries may develop resilience according to different phases or pathways, such as proactive, absorptive, adaptive, reactive and transformative. These are based on the type of unplanned event or sustainability challenges they need to overcome. Accordingly, it was seen that implementing I4.0 technologies may give rise to the building of specific resilience factors. Improving operational efficiency may help build robustness, improving agility in operations may build agility, transparent and visible information flows may make industries resourceful, business model innovation may build adaptability and, lastly, it was seen that improved flexibility within operations may build a flexible resilience response towards deriving sustainability benefits.

The results of the thesis were then used to formulate a holistic sustainability transitions model (Figure 13) based on an extension of the initial conceptual framework developed in the thesis (Figure 3). The use of the social science theories (as described in Chapter 3) in the model helped, not only in guiding the thesis but also in inductively finding patterns between the emerging theories in the research (Creswell, 2003). The enabling technologies of I4.0

depicted in the model are by no means the only technologies that may promote sustainability transitions. However, they were found to be the most-implemented technologies from the research findings.

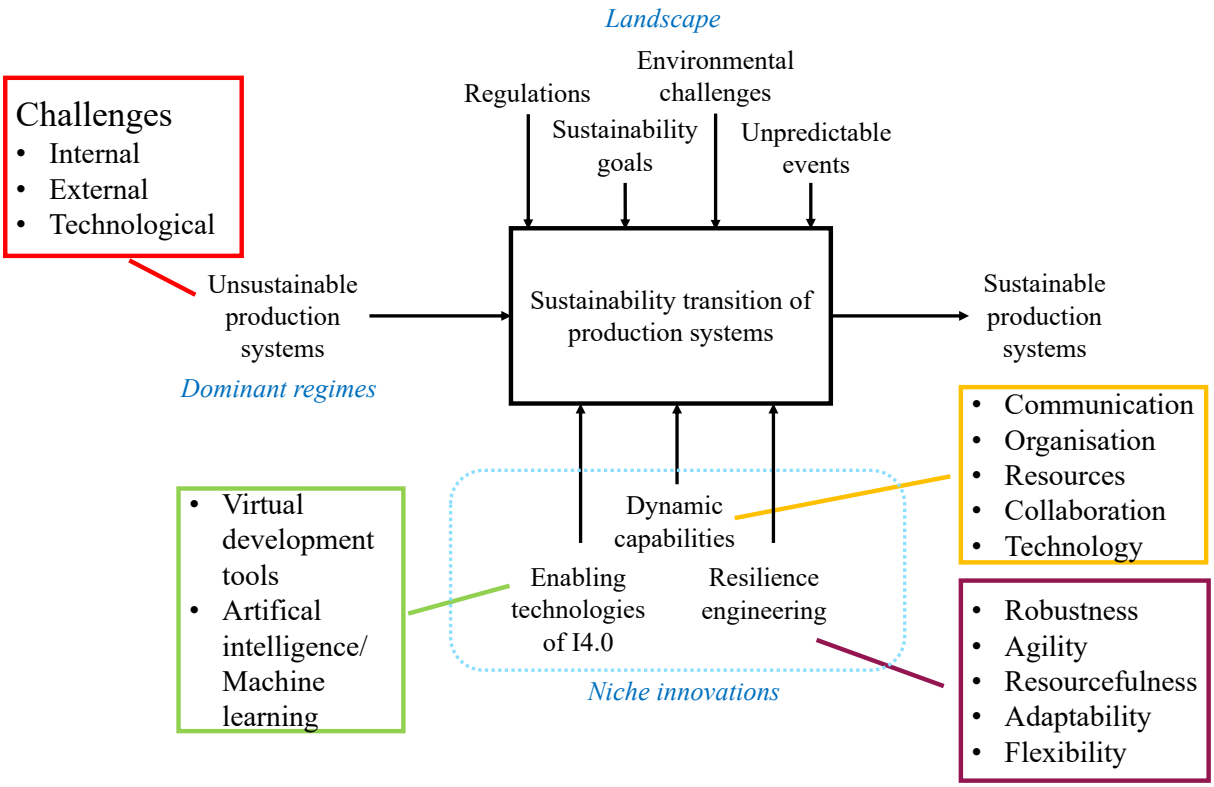

Figure 13. Proposed holistic sustainability transitions model.

5.4 RESEARCH CONTRIBUTION

5.4.1 Theoretical contributions

The industrial challenges identified in relation to RQ1 helped in understanding the systemic barriers with regard to industrial efforts towards sustainability, CE and the digital transition process. These challenges may help further scientific knowledge in developing more holistic solutions towards enabling sustainability transitions in this digital era. The thesis also explored the convergence of three emergent research areas for the context of sustainability transitions: Industry 4.0, dynamic capabilities and resilience engineering which may aid theory-building efforts. The convergence also pointed towards underlying connections between Industry 4.0 and dynamic capabilities, plus Industry 4.0 and resilience engineering concepts, all in the context of sustainability transitions.

5.4.2 Practical contributions

The author believes that our planet, with its limited resources, has final value and that humans have an instrumental role in restoring Nature, as much as possible, to the way they found it. This does not mean that humans' needs should not be met; it merely implies that humans need to limit their actions to maintain a properly functioning ecosystem. As a proponent of strong sustainability, the author suggests that a change in mindset first needs to come from us as individuals (and then society as a whole), if we are to influence industries to modify their production processes. Ultimately, the joint responsibility of different actors will have a higher

chance of success than assuming that the responsibility for sustainable development lies with the individual or with political solutions. Hence, the author would assert that complete radicalism in production operations is not always necessary and may not be sufficient to bring about long-term sustainable development. It may need to be complemented by incremental approaches (such as resilience) if it is to achieve successful sustainability transitions.

Therefore, based on the practical applicability of some of the research findings, the following recommendations are proposed to industrial practitioners:

- The model depicted in Figure 13 offers an insight into the holistic nature of sustainability transitions. The author hopes that industrial decision-makers and operators will find the model useful in gaining a holistic view of the systemic challenges that might impact the transition process, alongside the mechanisms that may help mitigate those challenges and support the transition of industry towards sustainability in the digital era.
- An important finding in the thesis was that stakeholders at multiple levels play an important role in green technology implementations that are part of sustainability transitions (in this case, in the textile industry domain) and their relevance must not be undermined. Figures 2, 6 and 8 may be useful in understanding the interplay of these influences at different stakeholder levels which may impact the sustainability transition process.
- The trade-offs between I4.0 technologies and corresponding sustainability benefits derived must be carefully considered before the implementation process. Table 5, which is based on theoretical and empirical findings, may give industrial practitioners an understanding of the different I4.0 technologies, their opportunities and corresponding sustainability/CE benefits and align them with their core business strategies.
- Dynamic capabilities may be used in decision support towards industrial sustainability transitions. The models depicted in Figures 8, 9 and 10 may be valuable tools in understanding the multidimensionality and interactions of dynamic capabilities. Furthermore, alongside the enabling microfoundations, they may help some industries gain a superior sustainable advantage compared to their competitors. Mapping dynamic capabilities may support industries and supply chains in their understanding of sustainability concepts and how to implement them to bring about successful transitions.
- Where fundamental changes in regime structures cannot take place, incremental methods such as resilience engineering strategies might be adopted if industries want to continue to steer towards successful sustainability transitions.

5.5 RESEARCH QUALITY

5.5.1 Internal validity

The following methods as prescribed by (Creswell, 2003, Yin, 2014, Creswell and Miller, 2000) were used to establish the internal validity or credibility of the research:

- *Triangulation of data:* to enhance the accuracy of the findings, data was examined using multiple forms of evidence – secondary data, participant perspectives from interviews, surveys and literature. All studies used more than two sources of data.
- *Member checking*: Lincoln and Guba describe this technique as 'the most crucial for establishing credibility' ((Lincoln and Guba, 1985), p.314). After thematising the data from the literature and expert studies in Paper II, the results were sent back to the

study participants to further comment on the data and to confirm the accuracy of the final findings. Member checking was also done in Paper III, in which eight survey participants were interviewed to corroborate the survey findings and go deeper in the analysis.

- *Cross-coder confirmation:* in Study C (Paper III), intercoder reliability was maintained (see Table 5) as the analysis used a well-structured coding method that was built and agreed upon by the authors of the paper (O' Connor and Joffe, 2020). This helped omit conflicts between collaborators.
- *Data saturation*: the themes that emerged from the nine expert interviews conducted in Study B (Paper II) were saturated and thus required no further data collection. Eight follow-up interviews were conducted in Study C (Paper III), to corroborate the initial findings in the study and explore how I4.0 technologies may build resilience towards sustainability. Since no additional information emerged after the interviews, no further interviews were conducted.

5.5.2 Reliability

The following strategies were used to check for qualitative reliability in the research approach (in other words, to check whether the findings were consistent or stable):

- *Compare or cross-check* individual results: the coding and data analysis were documented and shared on a regular basis with co-authors in all the studies, to ensure reliability of the findings.
- *Absence of errors in transcribed documents*: Study B (Paper II) required the transcription of nine interviews, each 60 minutes long. To ensure the absence of obvious mistakes in the transcription process, 'Otter.ai' (Otter Voice Notes, 2020) (AI software for transcribing audio files) was used. Manual editing and 'NVivo' (Hutchison et al., 2010), a qualitative data analysis tool, were also used to transcribe, store and thematise the data.

5.5.3 Generalisability

Generalisation uses techniques to establish the broader applicability of findings, but most often sees limited use in qualitative research (Creswell, 2003), as the goal of qualitative research is to gain insights into certain practices based on a particular context (Onwuegbuzie and Leech, 2009). Most qualitative studies use analytic generalisations or case-to-case transfer of findings (Miles and Huberman, 1994). Analytic generalisability is based on how concepts relate to each other and to theory, rather than to a population (as in the case of quantitative research). Case-to-case transfers refer to generalisations from one case to other, similar cases from certain points of view. Creswell (Creswell, 2003) also describes 'particularity' (meaning the themes or descriptions developed for specific contexts in qualitative research) as being a more important factor than just the generalisability of qualitative findings.

The themes and findings from Studies B and C (Papers II and III) contributed to theory development at the convergence of sustainability, Industry 4.0, dynamic capabilities and resilience engineering research fields. Study C (Paper III) used a cross-case study analysis, which included an industrial case sample of 78 manufacturing projects across Sweden, to examine the themes, similarities and differences across the diverse cases. Since Studies A and B (Papers I and II) used smaller samples and a specific industrial context (Paper I), it is difficult to claim generalisability of the findings. However, the research procedures used in the studies were documented in comprehensible and replicable fashion, using 'thick descriptions' (Lincoln and Guba, 1985).

5.6 LIMITATIONS AND FUTURE WORK

The main scope of this thesis included production systems and manufacturing supply chains. Within this scope, case studies were limited to the European subcontinent. Future work will focus on other geographical locations. Three relevant enablers supported by the literature and the UN's Green Deal were chosen to address the specific sustainability challenges derived in the thesis and support the industrial sustainability transition process. The choice of these enablers might have limited the type of findings that emerged in the studies. The research used data from a limited number of samples: a single case study in Paper I, and two case studies and nine interviews in Paper II. Although a larger sample might increase the quantity of results, additional data revealed no new insights (Creswell, 2003) in Paper II due to the novelty of the topics being considered. The challenges identified for a specific sector (in Study A, for instance, which was within the textile industry domain (Paper I)) may not be relevant to other sectors. This will need validation in other domains in future work.

Since I4.0 is an emergent research field, concepts such as IoT and CPS (especially concerning sustainability/CE) may have been understood differently by the different survey respondents in Paper III. Similarly, CE concepts were interpreted and implemented differently, as shown in Papers II and III. Future in-depth studies might help dispel the confusion regarding these topics and confirm the variety of terms used. Further, social sustainability benefits were not specifically reported by many manufacturing companies and some of these could not be isolated in Paper III. This might be because Sweden has a strong culture and long-standing awareness of ensuring good working conditions for its employees, factors which might easily have been taken for granted.

Although several different areas at the convergence of the main research topics were explored, various others require attention and will be explored in the next phase of the research. These are described below:

- Resistance to the enablers identified in the present work may impact the sustainability transition progress and these will be identified and measured.
- Some manufacturing industries (for the context of this thesis, the textile domain), are still at a nascent stage in terms of radical transformations. Suitable sustainability transition pathways based on industries' domain, size and capabilities will need to be explored.
- The type of event that impacts the sustainability transition process has a major impact on the corresponding resilience response. Hence, the dynamic and temporal aspect of resilience will be further studied.
- I4.0 opportunities to build industrial resilience to gain sustainability benefits will be further empirically tested at the production and supply-chain levels.
- The dynamic capabilities identified in the thesis will be further consolidated into a practical tool for industrial applications.

6

"The only stable thing is that everything changes"

– Heraclitus, Ancient Greek Philosopher

CONCLUSIONS

This chapter presents the conclusions of the thesis.

Manufacturing industries are currently operating on two, rather asynchronous, transition waves: the digital transition wave with Industry 4.0 and the sustainability transition wave. If we are to build a future with resilient production systems which can achieve long-term sustainability, it is imperative that manufacturing industries catch these waves synchronously and derive dual benefits from this transition. To reach this vision, the author used a pragmatic, mixed-methods research approach, entailing empirical and theoretical studies alongside two research questions. The aim was to understand the current systemic challenges that manufacturing companies face in becoming more sustainable, and to study the enabling mechanisms which may support the sustainability transition of manufacturing industries.

The initial studies aimed at understanding where manufacturing companies stand today in their sustainability transition efforts and what challenges need to be overcome. The key challenges emerging from the studies conducted in this thesis were summarised into three main categories: (i) **internal** (organisational routines, strategies and infrastructure; cultural mindset, financial structures, lack of skills); (ii) **external** (regulations, global policies, collaboration with stakeholders); and (iii) **technological** (data/information-type, quantity and quality, digital maturity levels). Lack of a consistent understanding of sustainability and I4.0 concepts at the firm level and in their value-chain partners was found to be at the heart of the other challenges that were discovered.

Next, three key enablers were identified to support industrial transition towards sustainability: (i) **Industry 4.0 technologies**, (ii) **dynamic capabilities** and (iii) **resilience engineering**. This choice was supported by the literature and the action plan proposed in the EU's Green Deal. In terms of I4.0 technologies, it was seen that *artificial intelligence/machine learning, virtual development tools and sensors* are largely being implemented in production contexts to derive triple bottom line sustainability benefits, such as improved resource efficiency, working conditions, extended product and machine lifetimes, reductions in costs and errors and the incorporation of circular economy practices. I4.0 opportunities were also seen to offer critical capabilities to overcome the collaborative challenges of digital supply chains. In terms of dynamic capabilities, *five microfoundations of dynamic capabilities* were derived which may help overcome the challenges to circular economy transition in the digital era: communication, organisation, resources, collaboration and technology. Regarding resilience, the opportunities derived from I4.0 were explored to build industrial resilience for sustainability and *five key resilience factors* were derived: robustness, agility, resourcefulness, adaptability and flexibility. These may allow industries to be proactive, absorptive/adaptive, reactive and transformative, depending on the firm's resilience response to sustainability challenges.

The research contributed to theory by applying a systemic approach in studying the convergence of emergent research topics which enable sustainability transitions. These included Industry 4.0, dynamic capabilities and resilience engineering. The research also contributed to practice by providing industrial practitioners with a holistic model describing the systemic challenges which can hinder sustainability transitions and the enabling mechanisms which can support it.

Despite the sustainability challenges faced by today's manufacturing companies, they are slowly but surely on the right track in their sustainability transition efforts in this digital era. Industry 4.0, sustainability and resilience are concepts which industries know about but still do not understand sufficiently. Moreover, a lack of a strong commitment to implementing these concepts will make the path towards sustainability transition a difficult one. The author hopes her research may contribute by supporting manufacturing companies in their sustainability transition process in the digital era.

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