THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Building manufacturing resilience for sustainability

- *a dynamic capabilities perspective*

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Cover:
Symbol of resilience - A collage depicting a factory amid turmoil, a beacon of hope against the storms of geo-political conflicts, pandemics, and climate crises. Credit for this collage goes to the author's talented colleague Huizhong Cao who created the drawings and collaged the elements in the image.

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ABSTRACT

In the contemporary Industry 4.0 era, manufacturing companies are faced with a simultaneous transition towards digital and sustainable transformations. Furthermore, many organisations have prioritised 'resilience' as part of their transformation agendas due to complexities resulting from the Covid-19 pandemic. Digitalisation, sustainability, and resilience thus form a 'triptych' in the manufacturing sector. This confluence includes multifaceted dimensions that are challenging for manufacturing organisations and their associated value chains to fully understand and operationalise. Thus, it is necessary to understand these complexities to exploit the related benefits and successfully address the pressing sustainability concerns currently faced by manufacturing companies. This thesis aims to provide manufacturing companies with concrete mechanisms to strengthen their resilience and understand its implications for sustainability. With this aim, and with sustainability as the key driver of building manufacturing resilience, the thesis focuses on: (1) conceptualising resilience and sustainability in the manufacturing context; (2) identifying enablers of manufacturing resilience for sustainability; and (3) developing assessment methods to build manufacturing resilience that favours sustainability.

Six studies were carried out over the last five years using a multiple-case study design and a mixed-methods approach. Data was triangulated in the form of systematic literature reviews, interviews, workshops and surveys. The thesis derived three main outcomes: (i) the relationships (synergies, conflicts and underlying concepts) between resilience and sustainability in manufacturing (*conceptualisation*); (ii) key *enabling* factors for building manufacturing resilience [*risk management*, *dynamic capabilities* that need to be developed in a stage-wise temporal manner for resilience (anticipation, coping and adaptation phases), and how *digitalisation in Industry 4.0* can support resilient and sustainable manufacturing]; (iii) an IDEF0 resilience model to structure and visualise the interconnectedness of and interdependencies between the enabling resilience factors. Also, a quantitatively validated measurement instrument – a resilience compass – to *assess* how manufacturing companies should deal with disruptions (operationalisation of resilience).

The theoretical contribution of this research is that it advances knowledge at the convergence of resilience engineering, dynamic capabilities and sustainability fields, especially in the smart manufacturing context. Practitioners can leverage the IDEF0 resilience model and the resilience compass to gain a comprehensive and systemic understanding of the various essential factors and capabilities across the temporal stages of resilience. This facilitates the formulation of tailored strategies to effectively address risks and disruptions and, ultimately, bolsters the resilience of both manufacturing operations and their value chains.

Keywords: resilience, dynamic capabilities, sustainability, manufacturing, value chains, Industry 4.0.

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Learning to get my driving licence to become an independent researcher (as my supervisors always reminded me!) involved several people to whom I am deeply grateful. Not only did they support me in completing my PhD studies, but they also helped me improve my resilience in dealing with the various risks that might have disrupted my journey.

Thank you, Ajja, my guru, my life. Your guidance and light have allowed me to trust in myself, blossom and be a better person each day.

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My deepest gratitude to my project partners from Produktion2030, TRUST, Digitala Stambanan and RE4DY. Your enthusiasm, collaborations and discussions have deeply enriched this research field. I am so grateful for your support and the wonderful friendships developed in the process. Jon, Carla, Denis, Sandra, Claudia, Maja, Magnus, Martin, Gabriella – your expertise made a huge impact in my work. I learnt so much from you and I am so glad we collaborated on the papers we wrote. Thank you!

A special thank you to Ebru. Your friendship, love and kindness will always have a special place in my heart. I am so grateful to have had your positivity and light. Your encouragement helped me believe in myself and do my best! Mahesh, thank you for your friendship and advice in helping me tackle the many challenges during my PhD. At the risk of missing out on naming all my friends and colleagues at the department, I would like to thank all of you for your support on this journey. Your laughter and energy reminded me that there is a lot more to life than just work. Thank you especially to Clarissa, Adri and Xiaoxia – I'm so glad we could support each other on our PhD journeys.

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I hope my research will enable me to 'walk the walk' and practice what I preach. I hope that starting this journey of sustainability and resilience from within will enable me to leave a positive 'handprint' on the only place we call home; the place that inspires me each day and which I will strive to protect in the years to come. The wonderful, glorious and ever-resilient, planet Earth.

APPENDED PUBLICATIONS AND WORK DISTRIBUTION

The following six papers are appended to this thesis (Papers I-VI) along with the contribution of the authors:

Paper I Gatenholm, G., Chari, A., Halldórsson, A., Stahre, J., (2021). *The intersection of industrial resilience and sustainability in manufacturing supply chains.* EurOMA Conference, Berlin, Germany (online).

Gabriella and Arpita designed the study and conducted the investigation, formal analysis and literature review. Gabriella wrote the main structure of the paper and Arpita provided support in the writing. Arni and Johan provided support in improving the overall structure of the paper and in the review process.

Paper II Chari, A., Niedenzu, D., Despeisse, M., Machado, C. G., Azevedo, J. D., Dias, R., and Johansson, B. (2022). *Dynamic capabilities for circular manufacturing supply chains – exploring the role of Industry 4.0 and resilience.* Business Strategy and the Environment. 31(5), 2500–2517. https://doi.org/10.1002/bse.3040.

Arpita designed the study, conducted the literature review and expert panel interviews, performed the data analysis and wrote the paper. Denis supported with conceptualisation and data analysis, provided his expertise on dynamic capabilities, reviewed the paper and provided feedback. Mélanie contributed to improving the illustrations and reviewed the paper. João and Ruis provided case study data, helped in the literature review process, reviewed the paper and provided feedback on industrial symbiosis. Björn Johansson reviewed the paper and provided feedback.

Paper III Chari, A., Duberg, J. V., Lindahl, E., Sudin, E., Stahre, J., Despeisse, M., Johansson, B. and Wiktorsson, M. (2021). *Swedish manufacturing practices towards a sustainable transition in Industry 4.0 – a resilience perspective.* ASME's Manufacturing Science and Engineering Conference, Ohio, USA (online). https://doi.org/10.1115/MSEC2021-62394.

Arpita designed the study with Johan Duberg and Emma. Together, they conducted interviews and carried out the survey analysis. Arpita also conceptualised the resilience concept for Industry 4.0 and sustainability, conducted the literature review and wrote the main structure of the paper. Johan provided support in the visualisations and co-wrote some sections of the paper. Emma provided her expertise on circular economy. Johan Stahre, Björn and Magnus reviewed the paper and provided comments. Mélanie helped improve some of the graphical illustrations, reviewed the paper and provided feedback. Erik gave support in the survey design and analysis, reviewed the paper and provided comments.

Paper IV Despeisse, M., Chari, A., González Chávez, C. A., Monteiro, H., Machado, C. G. and Johansson, B. (2022). *A systematic review of empirical studies on green* *manufacturing – eight propositions and a research framework for digitalised sustainable manufacturing.* Production and Manufacturing Research. 10(1), 727–759. https://doi.org/10.1080/21693277.2022.2127428.

Mélanie designed the study, wrote the main structure of the paper and created the visualisations. Arpita and Clarissa performed the initial screening of the articles. With Mélanie, they helped analyse the data and co-wrote many sections of the paper. Helena, Carla and Björn also helped with the data analysis and co-wrote some sections of the paper.

Paper V Chari, A., Stahre, J., Bärring, M., Despeisse, M., Li, D., Friis, M., Mörstam, M. and Johansson, B. (2023). *Analysing the antecedents to digital platform implementation for resilient and sustainable manufacturing supply chains – an IDEF0 modelling approach.* Journal of Cleaner Production. 429, 139598. https://doi.org/10.1016/j.jclepro.2023.139598.

Arpita Chari designed the study, collected data through workshops and interviews and analysed the data to create the IDEF0 model. Johan helped with the conceptualisation and co-wrote sections of the paper. Martin and Magnus collected data through Industry 4.0 maturity assessments at all three case companies and performed the analysis of this data. Dan provided his expertise on the Industry 4.0 Maturity Index section and provided overall feedback. Maja provided the case study data for the project. Mélanie and Björn reviewed the paper and provided overall feedback.

Paper VI Chari, A., Despeisse, M., Bokrantz, J., Johansson, B., Morioka, S., Gohr, C., and Stahre, J. *Dynamic capabilities for manufacturing resilience – a compass and industrial applications.* Submitted to a journal.

Arpita Chari designed the study, conducted the literature review, collected the data through workshops and interviews, chose the quantitative analysis method and wrote the paper. Mélanie provided feedback on the content and structure of the paper and helped in developing the visualisations for the compass. Jon contributed to the discussions on the methods used and gave overall feedback. Björn helped in the conceptualisation, reviewed the paper and gave feedback. Sandra and Claudia co-wrote some sections of the paper, especially on dynamic capabilities and provided overall feedback. Johan helped conceptualise the paper.

ADDITIONAL PUBLICATIONS

Chari, A., Despeisse, M., Johansson, B., Holgado, M. and Stahre, J. (2024). *Characterizing the relationship between environmental sustainability and resilience in manufacturing.* Submitted to the Advances in Production Management Systems (APMS) conference, Chemnitz/Zwickau, Germany.

Johansson, B., Despeisse, M., Bokrantz, J., Braun, G., Cao, H., Chari, A., Fang, Q., González Chávez, C. A., Skoogh, A., Söderlund, H., Wang, H., Wärmefjord, K., Nyborg, L., Sun, J., Örtengren, R., Schumacher, K. A., Espinal, L., Morris, K. C., Nunley, Jr. J., Kishita, Y., Umeda, Y., Acerbi, F., Pinzone, M., Persson, H., Charpentier, S., Edström, K., Brandell, D., Gopalakrishnan, M., Rahnama, H., Abrahamsson, L., Rönnbäck, A. Ö., Stahre, J. *Challenges and Opportunities to Advance Manufacturing Research for Sustainable Battery Life Cycles*. Submitted to the Frontiers in Manufacturing Technology journal.

Chari, A., Marti, S., Lopes, P. V., Johansson, B. Despeisse, M., and Stahre, J. (2023). *Modelling risk prioritization of a manufacturing supply chain using discrete event simulation.* Winter Simulation conference, Texas, USA.

González Chávez, C. A., Chari, A., Ito, A., Bärring, M., Friis, M., Mörstram, M. and Stahre, J. (2023). *Using digital platforms for value chain sustainability – Cases from the Digitala Stambanan project.* CIRP CMS conference, Cape Town, South Africa.

Despeisse, M., Johansson, B. Bokrantz, J., Braun G., Chari A., Chen X., Fang Q., González Chávez, C. A., Skoogh A., Stahre J., Theradapuzha Mathew N., Turanoglu Bekar E., Wang H., and Örtengren, R. (2023). *Battery Production Systems: State of the Art and Future Developments.* IFIP Advances in Information and Communication Technology, p. 521-535, Trondheim, Norway.

Syu F. S., Vasudevan A., Despeisse M., Chari A., Turanoglu Bekar E., Gonçalves M. M., Estrela M. A. (2022). *Usability and Usefulness of Circularity Indicators for Manufacturing Performance Management*. Procedia CIRP LCE conference, 105: 835-840, Leuven, Belgium.

Despeisse, M., Chari A., González Chávez, C.A., Chen X., Johansson, B., Garcia, I. G., Syberfelt, A., Abdulfatah, T., and Polukeev, A. (2021). *Achieving Circular and Efficient Production Systems: Emerging Challenges from Industrial Cases.* Advances in Production Management Systems (APMS) conference, 633: 523-533, Nantes, France (Online).

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

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LIST OF ABBREVIATIONS

DC – dynamic capability
SC – supply chain
VC – value chain
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

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I

“The real voyage of discovery consists not in seeing new sights, but in looking with new eyes.”

– Marcel Proust

INTRODUCTION

This chapter gives the reader a background of the research along with its vision and mission, followed by the research questions that will be addressed, and the delimitations.

1.1 BACKGROUND

"The greatest threat to our planet is the belief that someone else will save it" (Robert Swan, the first man to walk to both poles).

This unsettling assertion resonated with the author in her pursuit of a PhD. In the Anthropocene, humanity has emerged as a significant factor in shaping its own relationship with the Earth. Based on the findings of a recent study (Richardson et al., 2023), it has been determined that we have already exceeded six out of the nine planetary boundaries that ensure a safe environment for survival and uphold stability and resilience. These planetary boundaries are the Earth's environmental limits and include such factors as climate change, biodiversity loss and nutrient pollution. Apart from sensible consumerism (Koh and Lee, 2012), improved and responsible industrial production plays an equally important role in helping humanity operate within safe boundaries.

However, the manufacturing sector contributes one-fifth of global emissions and over 50% of the world's energy consumption (Vaskovich et al., 2023), making manufacturing companies vital players in meeting the 2030 Net Zero targets set by the European Commission (2019). A changing environment in which global sustainability is becoming more prioritised will require resilience (Fiksel, 2017). This is because risks (even with low probability) can cause severe disruption to manufacturing operations (Pires Ribeiro and Barbosa-Povoa, 2018). Risks (such as energy disruptions due to the recent Ukraine-Russia war, supply chain disruptions by the Covid-19 pandemic, extreme weather events from climate change, resource shortages, increased dependencies on senior skilled staff due to changing demographics and technological shifts in the current digitalisation era of Industry 4.0) all increase the vulnerability of manufacturing companies and their supply chains, whilst threatening the resilience of the planet.

With sustainability as the driving force of this thesis, resilience thus becomes an important way to effectively address ongoing risks and disruptions while also understanding corresponding sustainability implications. A fitting analogy would be going into battle (facing sustainability challenges) with armour (implementing resilient manufacturing practices). In the absence of resilience, manufacturing organisations face the risk of vulnerability and long-term survival difficulties when exposed to sustainability stressors.

Resilience refers to the ability of systems to prepare effectively for, cope with and recover from disruptions (Duchek, 2019), ultimately enabling those systems to function at improved levels. 'A product, process, or service contributes to sustainability if it constrains environmental resource consumption and waste-generation to an acceptable level, supports the satisfaction of important human needs and provides enduring economic value to the business enterprise' (Fiksel, 2003 p. 5330).

Thus, systems need to be designed to handle disruptions from unintended events or risks and become inherently 'resilient' with functionalities such as diversity, efficiency, adaptability and cohesion (Fiksel, 2003). Such characteristics may influence system performance and may also address sustainable development, whereby 'opportunities for continued innovation, growth and prosperity' (Fiksel, 2003 p. 5330) can be achieved.

The 'system' studied in this thesis is a manufacturing company or organisation in which products, processes (production, logistics, procurement and so on) and services interact with the broader systems within which they operate (including the supply chain, market, nature), to create value for their customers. By integrating resilient strategies and capabilities into their operations, manufacturing companies can better navigate disruptions and contribute positively to sustainability outcomes (Bag et al., 2019; Zavala-Alcívar et al., 2020).

Firstly, to build, strengthen or enhance the resilience of organisations and impact sustainability, we need to address a comprehension of resilience and its relationship to sustainability. However, the extant literature pertaining to this correlation (particularly within the context of manufacturing) is not well-established (Balugani et al., 2020; Rajesh, 2021). This deficiency arises from the interconnected and multidimensional nature of these concepts, another factor not adequately understood in industrial practice.

Secondly, advancing manufacturing resilience involves comprehending the enabling factors or building blocks that facilitate the creation of measurement or assessment tools for implementing resilience. Dynamic capabilities (DCs) have been effective in creating resilient systems (Pu et al., 2023; Sabahi and Parast, 2019) and contribute to sustainability in the long-term (Amui et al., 2017). The DC theory is built on the resource-based view of firms, which suggests that organisations can create value by possessing rare and valuable resources (Wernerfelt, 1984). However, value creation can only be realised when organisations accumulate, combine, exploit and deploy resources appropriately in a business environment (Sirmon et al., 2007). These dynamic capabilities are unique and difficult to replicate (Teece and Pisano, 1994). They give firms a competitive advantage in changing and uncertain environments. Organisations also have an opportunity to use such capabilities to adapt to and shape the environment (Teece, 2007). Thus, dynamic capabilities allow organisations to learn, improve and adapt (Amui et al., 2017) to sudden changes in the environment (Beske et al., 2014).

Although other organisational theories that jointly consider resilience and sustainability implementations have been studied (Rajesh, 2021), the dynamic capabilities theory was found to be a suitable foundational framework for the context of the present thesis, wherein manufacturing companies may need to cultivate capabilities to navigate risks, foster resilience, create value and contribute to sustainability in an uncertain and dynamically evolving environment.

1.2 VISION AND MISSION OF THE THESIS

Given the background described above, the **vision** of the thesis is for manufacturing companies and their supply chains to achieve long-term manufacturing resilience for sustainability. Thus, the author envisages a utopian future in which manufacturing companies and their supply chains can proactively prepare and efficiently respond to disruptions using automated strategies, whilst maintaining positive sustainability implications.

The author aims to realise her vision through a **mission** comprising two research objectives:

- To provide a contextualisation of the different aspects that encompass resilience and sustainability concepts in manufacturing.
- To establish mechanisms to build manufacturing resilience for sustainability.

1.3 RESEARCH QUESTIONS

With sustainability as the main driver and with the author's vision and mission in mind, this thesis aims to answer three research questions.

An important first step in building manufacturing resilience is a sound understanding of what resilience means in the manufacturing context and its relationship to sustainability. This was addressed by RQ1:

RQ 1) How can manufacturing resilience for sustainability be conceptualised?

As a next step, the enablers for building manufacturing resilience for sustainability needed to be identified. This was addressed by RQ2:

RQ 2) What enables manufacturing resilience for sustainability?

The enabling factors were considered as building blocks, whereby certain assessment tools were formulated to operationalise resilience in manufacturing companies and their supply chains. This helped in formulating RQ3:

RQ 3) How can manufacturing resilience be assessed?

The thesis adopted a multiple-case study research method, combining the usefulness of both qualitative and quantitative data to circumvent the subjective bias in the exploratory research field when studying the convergence areas of resilience, sustainability and dynamic capabilities.

1.4 SCOPE OF THE RESEARCH

This thesis has the following delimitations:

- The research focused on discrete manufacturing companies based predominantly in Europe. Future work will aim to broaden this scope to encompass diverse manufacturing domains and global locations. The results could also be applied in the process industry but this needs further exploration.
- The focus of the thesis or 'system' studied in this thesis is manufacturing companies or organisations. However, this system was also investigated in the broader context of the supply chain within which it operates. Thus, this thesis has borrowed from the supply chain management (SCM) and supply chain resilience (SCRES) fields to study manufacturing resilience.
- Several enablers may potentially influence the building of manufacturing resilience for sustainability. However, only those recurring factors which could address the gaps in the literature and practice were recognised as relevant and included in the research.
- Although a resilience measurement tool was developed using a mixed-methods approach, no metrics-based quantitative resilience assessment was conducted for this thesis.
- The thesis does not account for changing demographics, political systems or financial policies as risks with the potential to impact the development of manufacturing resilience.

1.5 STRUCTURE OF THE THESIS

The thesis is structured as shown in Table 1.

Table 1. Thesis structure.

Chapter	Approach (How)	Motivation (Why)	Key contents (What)
1 – ***Introduction***	Describes the background, vision and mission of the thesis, delimitations of the research and its structure.	To introduce the reader to the problem to be addressed by three RQs.	• Background. • Problem and research gap to be addressed. • Vision and mission. • Research questions: **RQ1**: How can manufacturing resilience for sustainability be conceptualised? **RQ2:** What enables manufacturing resilience for sustainability? **RQ3**: How can manufacturing resilience be assessed? • Delimitations of the research. • Thesis structure.
2 – ***Theoretical framework***	Explores the current knowledge in manufacturing resilience, sustainability and related fields through literature studies.	To study current knowledge regarding resilience and related concepts and find the research gap that needs to be addressed.	• Theoretical background of the key concepts: conceptualisation of resilience and sustainability; risk management; dynamic capabilities; digitalisation; resilience assessment methods. • Research gaps identified that will be addressed by the RQs.
3 – ***Research approach***	Describes the process by which the research was designed and conducted along with the different methods undertaken.	To apply a structured and well-grounded research design guiding the thesis' work. To understand the different philosophical assumptions and theoretical lenses that can be applied.	• Philosophical foundation. • Overview of the research design. • Research methods used in each study.
4 – ***Results***	Presents the aspects that need to be considered for conceptualising resilience, the different factors that contribute to building resilience and the mechanisms for building it.	To identify different factors and develop methods to address the challenges of understanding resilience and sustainability concepts from an empirical perspective. Application in case studies further cemented findings.	• Resilience conceptualisation (RQ1). • Resilience enablers (RQ2): dynamic capabilities, risk management, digitalisation. • Resilience assessment methods (RQ3): IDEF0 functional modelling approach and the resilience compass. • Synthesis of results.
5 – ***Discussion***	Reflects upon and interprets the research findings, how they answer the RQs, and how they relate to existing knowledge.	To showcase whether the mission of the thesis was achievable by answering the RQs. To highlight the implications of the thesis	• How the research relates to previous work and contributions. • Implications for theory and practice. • Research quality. • Limitations and future work.
6 – ***Conclusion***	Provides the key contributions of the thesis.	To summarise the key takeaways of the thesis.	Significant research contributions based on observed challenges.

2

"In theory, there is no difference between theory and practice. But, in practice, there is."

– Benjamin Brewster (1882)

THEORETICAL FRAMEWORK

The following chapter seeks to briefly describe the key concepts and theories that guided the research, with particular emphasis on conceptualisation, risk management, dynamic capabilities, digitalisation in Industry 4.0 and resilience assessment methods. The rationale of this chapter is to find a theoretical underpinning and connection of these concepts, to understand how they help strengthen manufacturing resilience for sustainability.

OVERVIEW

Manufacturing firms face disruptions (including plant shutdowns, production stoppages and delayed shipments) due to unforeseen risks like natural disasters due to climate change, resource scarcity, geo-political tensions and so on. This necessitates the cultivation of manufacturing resilience, whereby companies can navigate, cope with and recover from such disruptions.

Based on a semantic reference system, Daniel (2011) created a resilience ontology to operationalise resilience and its underlying terms. van Wassenaer et al. (2021) applied the identified resilience aspects to food systems; these were then compared with this thesis' context of manufacturing resilience (italicised in the list):

- Managing resilience: *through risk management.*
- Resilience to what: *disruptions.*
- Resilience of what: *manufacturing companies.*
- For what purpose: *to enable sustainability outcomes.*
- Measuring resilience: *through dynamic capabilities.*

Thus, the resilience of such manufacturing systems can be realised when risks and corresponding disruptions are identified (Daniel, 2014) and dealt with accordingly (through dynamic capabilities, as proposed in this thesis) to bring about a pre-defined outcome (to enable sustainability – the driver of this thesis).

However, there has been a paucity of comprehension regarding the requisite parameters for commencing the design of resilient production systems. According to Srinivasan et al. (2016), the initial phase of disruption identification – a component of *risk management* – serves as a viable starting point. This can subsequently pave the way for the formulation of pertinent *capabilities* (Bag et al., 2019; Chari et al., 2022; Parker and Ameen, 2018) and *strategies* (Golicic et al., 2017; Reyes et al., 2023) essential for achieving resilient manufacturing. Incorporating resilience capabilities and strategies has proved to not only improve organisational performance but also contribute positively to sustainability (Sarkis et al., 2020).

Before formulating such capabilities and strategies, it is crucial to undertake the *conceptualisation* of resilience and sustainability. This entails the unravelling of multiple terminologies and concepts that make up these larger umbrella concepts (Ponomarov and Holcomb, 2009) as well as the similarities and trade-offs that exist between them (Marchese et al., 2018; Zavala-Alcívar et al., 2020). In addition, the implementation of *Industry 4.0 technologies* in manufacturing practices has demonstrated the potential for fostering the development of resilient and sustainable supply chains (S. Bag et al., 2021; Nandi et al., 2021). Hence, the thesis has centred its attention on the above concepts; these provided a theoretical framework for conducting the research and are further described in Sections 2.2-2.6. Each of these concepts is elucidated in the sections shown in Figure 1.

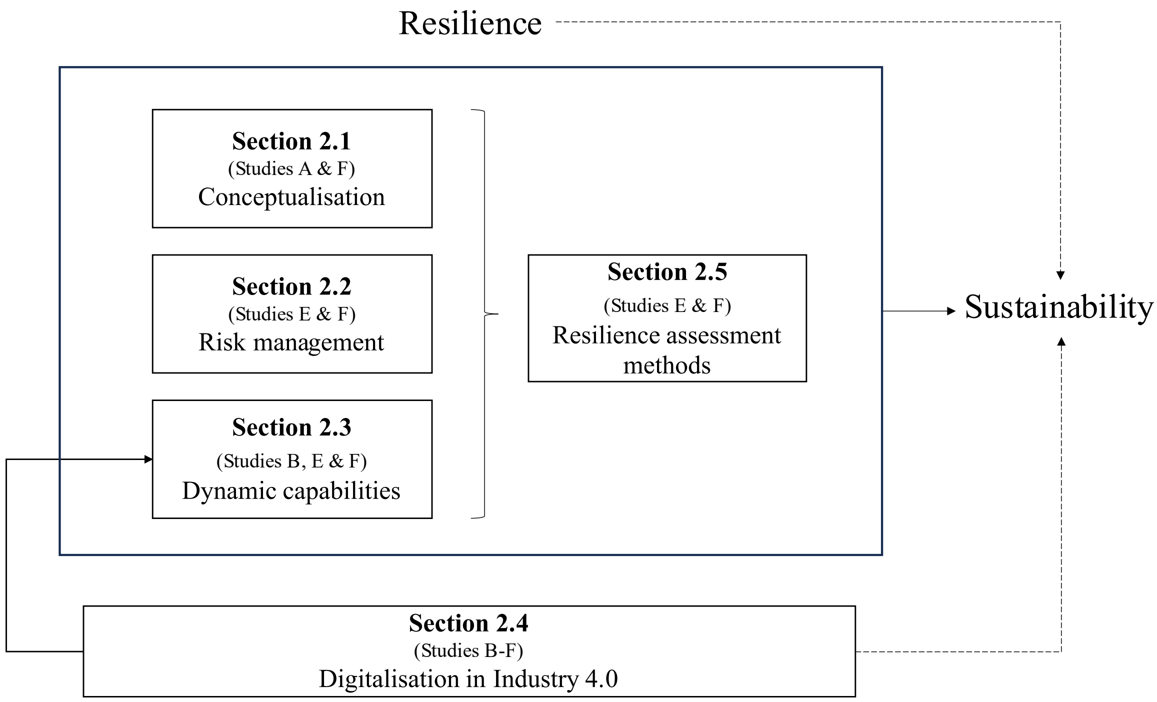

Figure 1. Theoretical framework guiding the thesis.

An overview of the different concepts used in the thesis and their definitions is summarised in Table 2.

Table 2. Definitions of concepts used in the thesis.

Concept	Definition
Sustainable development	Meets the needs of current generations without compromising the ability of future generations to meet their own needs (United Nations World Commission on Environment and Development, 1987).
Sustainable manufacturing	A new paradigm for developing socially and environmentally sound techniques to transform materials into economically valuable goods (Despeisse et al., 2012 p. 355).
Resilience	The ability to anticipate potential threats, cope effectively with adverse events and adapt to changing conditions (Duchek, 2019 p. 220).
Anticipation	The ability to identify potential risks and take proactive steps to ensure that an organisation thrives in the face of adversity (Somers, 2009 p. 19).
Coping	The systemic capability of socio-technical systems to accommodate the effects of change stressors (Amadi-Echendu and Thopil, 2020).
Adaptation	The ability of a system to return to its original state or move to a new, more desirable one after being disturbed (Christopher and Peck, 2004 p. 4).
Redundancy	Involves maintaining excess capacity, safety stock, multiple suppliers and backup sites (Han et al., 2020).
Robustness	The capacity of a system to tolerate disturbances while retaining its structure and function (Fiksel, 2003).
Situation awareness	The ability to sense and forecast a possible disruption through knowledge of organisation/supply chain vulnerabilities, the sharing of information and corresponding activities (Han et al., 2020).
Visibility	The acquisition and evaluation of information to: enable transparency and awareness of the current supply chain situation; trace the points of origin of entities; control disruption risks; and improve decisions (Lee and Rammohan, 2017).
Security	Involves personnel security, physical security and cyber-security (Han et al., 2020).
Agility	The ability to rapidly respond to unpredictable changes in supply or demand in the marketplace, since customer requirements are continuously changing) (Han et al., 2020).
Flexibility	The ability to adapt and adjust to a disruption, rather than merely withstand the damage from it (Han et al., 2020).
Collaboration	The exchange of information and application of shared knowledge to decrease uncertainty (Han et al., 2020).

Leadership	The implementation of management in companies. This requires support from senior management, employee engagement and high-quality decision-making (Han et al., 2020).
Knowledge management	The ability to learn from feedback after a disruption to develop better plans and solutions for future ones (education, training and innovation) (Han et al., 2020).
Contingency planning	Involves supply chain reconfiguration, scenario analysis and resource reconfiguration to help organisations recover and learn from disruptions (Han et al., 2020).
Market position	Related to knowledge about financial perspectives, including financial strength, market share, cost-efficiency and loss absorption (Han et al., 2020).

2.1 RESILIENCE AND SUSTAINABILITY IN MANUFACTURING AND SUPPLY CHAIN LITERATURE

Resilience has its roots in ecology, with Holling (1973 p. 14) describing 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'. Stability of the system was key here, with systems able to bounce back to equilibrium states and persist in the presence of a temporary disturbance ('robustness', as it is commonly known). The same approach has been adopted in engineering. Engineering resilience 'concentrates on stability near an equilibrium steady state, where resistance to disturbance and speed of return to the equilibrium are used to measure the property' (Holling, 1996 p. 33). Hollnagel et al. (2010) also emphasised systems' return to steady-state conditions.

However, manufacturing supply chains cannot be regarded as mere engineered systems with static encompassing components, as depicted in most supply chain management literature (Wieland and Durach, 2021). An SC is a more complex system and is part of a broader 'network of connected and interdependent organisations mutually and co-operatively working together' (Christopher, 2016 p. 3) that are influenced by its environment and the social actors functioning within it. Wieland and Durach (2021) called this the social-ecological perspective of resilience. In other words, SCs cannot be isolated from the environment and can be considered as systems of systems (Wieland, 2021), which are dynamic and constantly evolving through social actor interactions. Wieland and Durach (2021) defined supply chain resilience as 'the capacity of a supply chain to persist, adapt, or transform in the face of change'. They concluded that supply chains operate as open systems, emphasizing that resilience should encompass not only stability but also the capacity for adaptation and transformation.

Supply chain management has since adopted resilience mechanisms to improve SC performance (Christopher and Peck, 2004; Sheffi and Rice, 2005) but many studies focus mostly on the narrower 'engineering' approach to resilience. Supply chain resilience (SCRES) is a phenomenon that only became popular in the early 2000s (Ali et al., 2017), with resilience regarded as a larger umbrella concept. Not only does it help organisations deal with disruptions arising due to risks, it also learns from them and brings about better operational states (Fiksel et al., 2015). Ivanov (2023) viewed supply chain resilience from two perspectives: stability-based (similar to ecological resilience, where the focus is on performance deviations in systems) and adaptive-based (an embedded system property used for emergency disruption scenarios AND business-as-usual operations, in which the focus is on performance persistence or viability in systems). Ivanov (2023) suggests balancing both to manage supply chain disruptions; the hindsight-driven stability view of resilience and the foresight-driven adaptability view of resilience.

Resilience research spans various disciplines such as management, ecology, sociology and engineering. Ruiz-Martin et al. (2018) described several areas that influence organisational resilience, such as resilient individuals, resilience engineering processes, supply chain resilience, system resilience and so on. These, in turn, influence the resilience of other areas such as community resilience, societal resilience, socio-ecological resilience and the like. However, even within these domains, consensus remains elusive regarding the definition, interconnections and metrics of resilience (Bhamra et al., 2011; Christopher and Peck, 2004). Although resilience is not a recently conceptualised phenomenon, it comprises several underlying factors and mechanisms.

Resilience terminologies are vague due to the multiple concepts surrounding them (Bhamra et al., 2011; Ponomarov and Holcomb, 2009), especially in the manufacturing context. Thus, resilience is a dynamic, multidimensional concept (Adobor and McMullen, 2018), which may require capabilities at different temporal stages; before, during and after a disruption (Conz and Magnani, 2020; Duchek, 2019; Han et al., 2020). To navigate the different resilience terminologies and understand their historical evolution, the occurrence of these terms was checked in the Scopus scientific database, in publications post-1970 (after Holling (1973) formally described ecological resilience) and up to 2023. The search strings used are shown in Table 3.

Table 3. Search criteria for resilience terminologies in Scopus *(only English articles within the engineering, business and decision sciences fields were considered)*.

No.	Search string
1	resilien* AND (manufactur* OR production)
2	resilien* in (1) replaced with flexib*, agil*, adaptab*, resourcefulness, robust*, visib*, redundan*, and transparen*

Figure 2. shows that ‘flexibility’ and ‘redundancy’ were the most-used terms and that the term ‘resilience’ itself (in black) is not so commonly used. All terms see a sharp increase after 2020, which is not surprising considering that manufacturing was severely impacted by the Covid-19 pandemic. Too few articles were found for ‘resourcefulness’ and was hence omitted in Figure 2. Several articles may have been cited multiple times, potentially with two or more relevant terms in their publications. However, the paramount observation lies in these trends offering insight into the significance of diverse terminologies and the imperative to elucidate their interconnections. Additionally, it is crucial to note that other pertinent factors or elements may be influencing organisational resilience but may not have been included in the search.

However, numerous relationships among the above resilience terminologies exhibit conflicting interpretations in the literature. For instance, Pettit et al. (2013) and Sabahi and Parast (2019) considered flexibility to be a capability that enhanced the overall resilience of firms, while Singh et al. (2013) illustrated how dynamic capabilities can build the flexibility of firms and did not describe the term ‘resilience’ in their work. Hosseini et al. (2022) and Pettit et al. (2013) considered ‘adaptability’ and ‘recovery’ to be resilience capabilities, whereas Conz and Magnani (2020) and Duchek (2019) examined the terms in the context of temporal resilience phases. Some definitions of ‘resilience’ according to the different temporal phases were identified from the literature and are provided in Table 4.

While certain definitions incorporate resilience phases and others do not, this thesis’ findings underscore the importance of recognising three distinct resilience stages in systematically building resilience. As part of business-as-usual planning activities, Ivanov (2023) emphasised preparing for disruptions, responding to disruptions and learning. He called these adaptability-based view responses (proactive and reactive approaches to resilience). This thesis focuses on designing resilient manufacturing systems by developing dynamic capabilities. This is consistent with the adaptability-based view which views resilience as a property designed to make systems structurally adaptable to disruption. With the emphasis on embedding resilience in manufacturing systems, the author has used the three-stage temporal definition of resilience offered by Duchek (2019) to develop resilience capabilities: ‘the ability to **anticipate** potential threats, **cope** effectively with adverse events and **adapt** to changing conditions’.

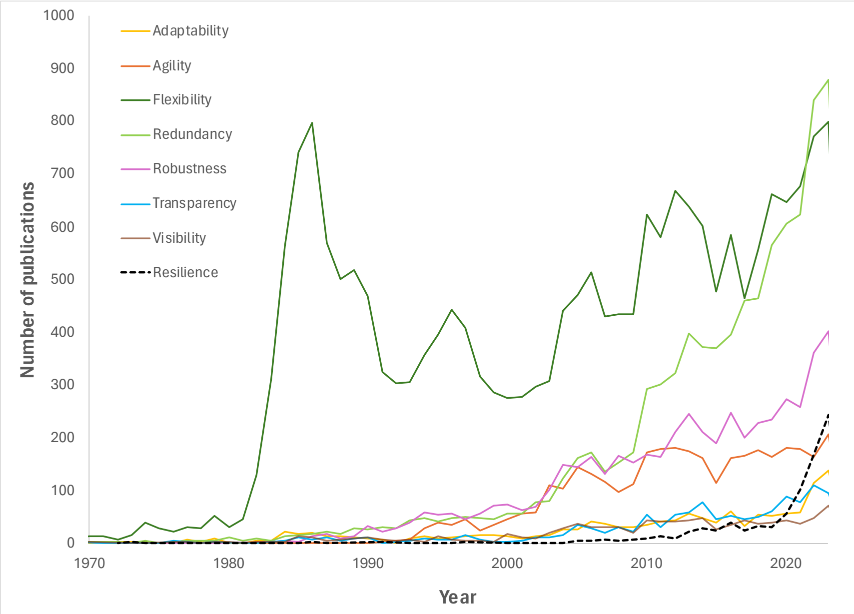

Figure 2. Resilience terminologies used in the literature.

The proactive or pre-disruption stage at time t-1 is known as the anticipation, readiness or detection phase, in which companies prepare for disruptions by identifying potential risks (from different sources and varying frequencies, severities and impact boundaries); the coping or concurrent stage at time t is when disruptions occur and organisations need to cope with or respond to them; and the reactive or post-disruption stage at time t+1 is when organisations need to adapt, recover and learn after the disruption has occurred (Figure 3).

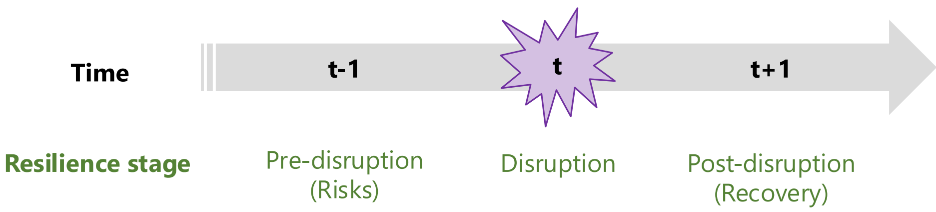

Figure 3. Resilience stages according to time.

There is also no consensus in the literature on the ‘focus’ or ‘trigger’ event in resilience (Pires Ribeiro and Barbosa-Povoa, 2018). For instance, risks are sometimes known as threats (Bhamra et al., 2011), unintended (World Economic Forum, 2023) or unexpected events (Fiksel, 2017); disruptions are also called disturbances (Burnard and Bhamra, 2011) and other such terms. This thesis uses the following terms: ‘risks’ are events that make organisations vulnerable, which in turn could give rise to disruptions. Thus, ‘disruptions’ are manifestations of risks and risks may exist in organisations without causing disruptions (DuHadway et al., 2017).

Additional descriptions of the different temporal resilience phases and conflicting resilience terminologies found in the literature appear in Paper VI.

Table 4. Resilience definitions from the literature, according to the temporal resilience phases (Adapted from Study F, Paper VI).

Resilience stage	Definition	Reference
Anticipation/readiness/ detection *(proactive or pre-disruption phase, time t-1)*	The ability to anticipate and overcome supply chain disruptions.	(Pettit et al., 2010 p. 6)
	The ability to identify potential risks and take proactive steps to ensure that an organisation thrives in the face of adversity.	(Somers, 2009 p. 19)
	The incremental capacity of an organisation to anticipate and adjust to the environment.	(Ortiz-de-Mandojana and Bansal, 2016 p. 1617)
Coping/response *(concurrent or disruptive phase, time t)*	The capacity of organisations to cope with unanticipated dangers after they have manifested.	(Weick et al., 1999; Wildavsky, 1988)
	The systemic capabilities of socio-technical systems to accommodate the effects of change stressors.	(Amadi-Echendu and Thopil, 2020)
	The ability to respond to disruptions and restore normal operations.	(Rice and Caniato, 2003 p. 22)
Adaptation/learning/ recovery *(reactive or post-disruptive phase, time t+1)*	A firm's ability to recover from supply chain disruptions quickly.	(Blackhurst et al., 2011 p. 374)
	The ability of a system to return to its original state or move to a new, more desirable state after being disturbed.	(Christopher and Peck, 2004 p. 4)
	The capacity of an organisation to survive, adapt, sustain and equip the business in the face of turbulent change.	(Ates and Bititci, 2011 p. 5601)
Other overlapping definitions		
Robustness	Implies self-regulation and resistance to disturbances of a system.	(Heinicke, 2014 p. 202)
	The capacity of a system to tolerate disturbances while retaining its structure and function.	(Fiksel, 2003)
Anticipation, adaptation	The ability to prevent supply chain interruption and possibly recover normal operating conditions quickly, even after suffering from heavy disruptions.	(Bag et al., 2019 p. 866)
Coping, adaptation	The measurable combination of characteristics, abilities, capacities or capabilities that allows an organisation to withstand known and unknown disturbances and still survive.	(Ruiz-Martin et al., 2018)
	The capacity of a supply chain to persist, adapt or transform in the face of change.	(Wieland and Durach, 2021 p. 316)
Anticipation, coping, adaptation	The ability to anticipate potential threats, cope effectively with adverse events and adapt to changing conditions.	(Duchek, 2019 p. 220)
	The capacity of an enterprise to survive, adapt and grow in the face of change and uncertainty.	(Pettit et al., 2013 p. 47)

A resilient organisation has a mixture of capabilities and practices that must be performed (Gibson and Tarrant, 2010) to achieve long-term sustainability. However, there is a lack of consensus in the literature regarding the correct terminology in this context. Do resilience capabilities require the development of certain practices, actions or sub-factors which, in turn, fall under a specific temporal resilience strategy or vice-versa? Negri et al. (2022) contribute to this area by categorising SC resilience practices and their relationship to the triple bottom line of sustainability.

According to Zollo and Winter (2002), dynamic capabilities will need to be developed from an organisation's own routines and practices. Although some other authors (Adobor and McMullen, 2018; Ali et al., 2017; Han et al., 2020) also provide some categorisations of the above terms, they still require further investigation, especially concerning empirical validations. This thesis helps unravel these terminologies and aids the development of capabilities, practices and stages for resilience.

In terms of the relationship between resilience and sustainability, the literature is primarily *resilience-dominated*, with fewer specifics on sustainability outcomes (Rajesh, 2019; Soni and Jain, 2011). If sustainability is considered, then it is centred primarily on the economic dimension of the triple bottom line (Carvalho et al., 2014; Jabbarzadeh et al., 2018). Some examples of *synergies* found between the two concepts were: innovative value propositions and business models that reduced environmental impacts and improved the resilience of supply chains (Schaltegger, 2020); proactive resilience strategies that had a positive impact on green supplier integration and resource efficiency (Ji et al., 2020); and localisation of supply chains that led to increased visibility and flexibility (Nandi et al., 2021). Some *conflicts* were also observed, such as increased social and environmental sustainability that gave rise to less robust supply chains (Jabbarzadeh et al., 2018) and an increase in buffer mechanisms that gave rise to increased waste (Carvalho et al., 2014).

Studies A and F further describe this topic of conceptualising resilience and sustainability. Details can be found in Papers I and VI.

Resilience may also be seen as a process, outcome or trait (Almedom, 2013; Gibson and Tarrant, 2010; Ivanov, 2023) based on the goals of an organisation. Sustainability is also described as a goal or a process with several underlying terms making up this concept (Moldavska and Welo, 2017). This makes resilience measurement or assessment for sustainability complicated and indicates a need for holistic measurement tools (described later in Section 2.6).

2.2 RESILIENCE AND RISK MANAGEMENT

Manufacturing companies are susceptible to risks and these may arise (with varying frequency severity, duration and type) from within or outside organisational boundaries (Brusset and Teller, 2017). Risks may be defined as the probability of unanticipated events leading to a direct or indirect disruption in the supply chain, rendering it susceptible (Christopher and Peck, 2004). Some risks can be known and planned for, while others fall under the known-unknown or unknown-unknown categories (black swan events) (Ivanov, 2023). Disruptions, on the other hand, are often difficult to predict and can be sources of uncertainty in an organisation (DuHadway et al., 2017). ‘Disruptions’ refer to events that disrupt regular operations, resulting in disorder and discontinuity, such as operational contingencies, production halts or financial instability (Madni and Jackson, 2009).

Risk management reduces the probability of a negative event occurring (Um and Han, 2020) and affects the performance of organisations (Altay and Ramirez, 2010). Its overall activities should address various aspects (Sodhi et al., 2012) such as risk identification, risk assessment, risk mitigation and response to disruption. Organisations would then need to develop suitable capabilities and response mechanisms (Bustinza et al., 2016; Duchek, 2019; Teece et al., 2016) to deal with disruptions.

Supply chains are open systems that interact with the environment (Pettit et al., 2013) and multiple concurrent risks may emerge unexpectedly. Hence, risk management should include not only the manufacturing firm in focus but also the supply chain of which it is a part, as the strength of an organisation (in terms of how it handles risks) is determined by the weakest link that connects a company to society at large. Localised problems may create ripple effects (Dolgui et al., 2018) across extended networks or supply chains and the capability of a company to withstand such disruption will ultimately determine its resilience (Starr et al., 2003).

Risk management practitioners adopt resilience concepts to withstand and adapt to changing and ‘new risk environments’ (Starr et al., 2003). Starr et al. (2003) describe how companies and their supply chains are exposed to interdependent risks – ‘unanticipated risk exposure across the extended enterprise that is beyond an individual organisation’s direct control’ which can impact its performance, reputation, operations and share price.

As mentioned before, resilience extends beyond traditional risk management methods and focuses on systemic characteristics (Wieland and Durach, 2021). This may require the development of capabilities by implementing organisational routines or practices (Brusset and Teller, 2017). Indeed, Christopher and Lee (2004) suggested that a sound supply chain risk management culture is an important antecedent or enabler of supply chain resilience. However, conventional risk management methods may be ineffective in addressing challenges relating to customer satisfaction and profitability. This was especially so during the Covid-19 pandemic (Agarwal et al., 2020). These authors proposed the integration of resilience into manufacturing supply chains as an alternative solution.

Study E provides additional information on the topic of risk and its relationship to building manufacturing supply chain resilience. Details of this appear in Paper V.

2.3 DYNAMIC CAPABILITIES

The dynamic capabilities theoretical framework, which is grounded in the resource-based view of firms (Wernerfelt, 1984) has been widely accepted as a means of improving the performance (Birkie and Trucco, 2020) and competitive advantage of organisations (Barreto, 2010; Teece et al., 1997) by successfully innovating and capturing value (Teece, 2007). According to Teece et al. (1997), a dynamic capability is characterised by its capacity to dynamically integrate, construct and reconfigure lower-level competencies in alignment with evolving business environments.

Dynamic capabilities are high-level routines that can help develop mitigation actions in the different resilience stages. Several such temporal resilience pathways appear in the literature (Studies C and F contain a detailed description) but the present research used the resilience stages defined by Duchek (2019) who categorised them as anticipation, coping and adaptation. These are congruous with the microfoundations of sensing, seizing and transforming dynamic capabilities. Indeed, Teece et al. (2016) described how these microfoundations of dynamic capabilities can deal not only with known risks but also uncertain threats, thus contributing to organisational resilience.

Previous research identified a firm’s innovativeness (Golgeci and Y. Ponomarov, 2013; Sabahi and Parast, 2019), technological capabilities (Surajit Bag et al., 2021; Bustinza et al., 2016; Dubey et al., 2021), remanufacturing (Bag et al., 2019), openness (Ahn et al., 2018) as relevant dynamic capabilities for building resilience in manufacturing organisations.

However, the literature is currently sparse when it comes to identifying such capabilities and categorising them within the temporal resilience pathways. Dynamic capabilities are also contingent on context and cannot be universally applied in a one-size-fits-all approach for value creation (Brusset and Teller, 2017). Moreover, Duchek (2019) pointed out that resilience stages may not be mutually exclusive and that capabilities may be interrelated and categorised under more than one stage (Adobor and McMullen, 2018; Chari et al., 2022). Resilience is therefore not an abstract catch-all term (Matyas and Pelling, 2015) but has a strong foundation for building capabilities so that 'resilience thinking' (abstract) can be transformed into 'actionable strategies' (operational). A thorough understanding of resilience, its associated terminologies and stages may help practitioners use suitable mitigation strategies to enhance the resilience of their firms and supply chains.

Study B provides further details on how dynamic capabilities were used as the underlying theory for the research in the thesis. Studies B, E and F described the categorisation of dynamic capabilities in accordance with the different resilience stages, details of which can be found in Papers II, V and VI.

Industry 4.0 technology implementation offers many opportunities to facilitate the development of dynamic capabilities, help with value capture and improve the resilience of organisations, whilst contributing to the triple bottom line of sustainability. This is described in the following section.

2.4 DIGITALISATION FOR RESILIENT AND SUSTAINABLE MANUFACTURING

As described in Chapter 1, the escalating global population is depleting resources at an accelerated pace and economic growth cannot be maintained on a planet with limited resources (Krautkraemer, 2005). Tighter environmental regulations, changing customer expectations, resource scarcity and associated risks in supply, climate change stressors and the like have forced manufacturing companies and their global supply chains to innovate and seek alternative, greener solutions. Digital technologies can generate new opportunities to create value for companies in complex ecosystem networks (Lee et al., 2015) and support sustainable manufacturing (Stock and Seliger, 2016). Indeed, balancing the dimensions of the triple bottom line of sustainability (economic, environmental and social aspects) is critical for successful technological adoption and for obtaining sustainability benefits (Müller et al., 2018).

We are currently in the Industry 4.0 (I4.0) digital era or the Fourth Industrial Revolution, which can be described as 'the digital transformation of the manufacturing industry, which is accelerated by exponentially growing technologies…[]' (Blunck and Werthmann, 2017). The I4.0 paradigm, a smart manufacturing context within which this thesis sits, is a term coined in 2011 based on the German term 'Industrie 4.0', which described the advancement of German manufacturing (Kagermann, 2013). The term encompasses the transformation of industries into smart connected factories connecting not only people and machines but also machines and other machines. This internet-based connectedness, which comprises such objects as RFIDs, sensors, actuators and the like that interact with each other and with neighbouring smart components (Hermann et al., 2015), is also known as the Internet of Things (IoT). These 'collaborating, computational elements use shared information to independently control physical entities' (Minerva et al., 2015) and are known as cyber-physical systems (CPS) (Monostori et al., 2016).

Various technologies can be associated with I4.0, such as collaborative robots, data-driven digital platforms, simulation models, edge computing, digital twins, virtual development (VD) tools, blockchain, big data analytics, artificial intelligence and machine learning. In terms of contributing to sustainability, digital twins can help optimise sustainability performance and address data availability issues, even beyond factory gates (Barni et al., 2018). Smart data from intelligent, cross-linked modules in I4.0 can help develop new, sustainable business models and value-creation opportunities for companies (Stock and Seliger, 2016). Blockchain has been known to facilitate circular economy practices (Esmaeilian et al., 2020) amongst other things.

I4.0 technology implementation has also been shown to provide multiple opportunities for developing resilience capabilities which, in turn, could have a positive impact on sustainability. The possibilities of I4.0 technologies to strengthen resilience and positively impact sustainability are many. From an increase in collaboration, data and knowledge-sharing in supply chains through cloud platforms (Fisher et al., 2018), to the use of big data and supply chain analytics for sustainable and resilient manufacturing (Raut et al., 2021). This is especially so concerning uncertainty in products' use and end-of-life management (Zhu et al., 2018) and the traceability and circular economy benefits of blockchain (Nandi et al., 2021), to increased production flexibility from using VD tools such as VR/AR (virtual and augmented reality). These allow workers to participate in complex tasks (Büchi et al., 2020), data-driven digital platforms for increased collaborative capabilities (Guo et al., 2021; Simoes et al., 2013; Tan et al., 2022) and improved information sharing and cyber threat detection.

Despite an awareness of the global impact of unsustainable methods of production and consumption and the potential of I4.0 technologies to enable sustainable manufacturing, few studies have validated its relevance empirically. Studies B and D (Papers II and IV) provide the contextual background to showcase the relevance of Industry 4.0 in meeting the goals of sustainable manufacturing while Studies C, E and F (Papers III, V and VI) give an empirical description of how I4.0 technologies can be used to improve the resilience and, hence, the sustainability of operations by developing dynamic capabilities.

2.5 RESILIENCE ASSESSMENT METHODS

After conceptualising resilience and its underlying factors, it then becomes important to assess resilience in manufacturing companies to understand its implementation levels and progress towards resilient, sustainable manufacturing. Although studies have provided quantitative models (Caputo et al., 2019), risk assessment methods (Tah and Carr, 2001), resilience assessment tools (Pettit et al., 2013; Zhang and Sharifi, 1999) and so on, few have empirically investigated the usefulness of such methods in 'holistically' measuring resilience (which consists of temporal stages) and how these can be implemented.

The literature has called for the development of rigorous tools for benchmarking and self-assessment to aid organisational learning and process improvement (Voss et al., 1994). In terms of resilience, The British Standards Institution (2022) emphasises models that can demonstrate not only an organisation's current resilience practices (what it 'has') but also its embedded capability or potential (what it 'can' do). These resilience practices should be bundled for the development of dynamic capabilities (Pu et al., 2023) in the temporal stages of resilience (Conz and Magnani, 2020; Han et al., 2020) and be used to deal with risks and corresponding disruptions. This will determine which organisations are more adept at managing crises compared to their competitors (Duchek, 2019). However, many of these studies have not quantitatively developed and empirically confirmed the capabilities, practices and corresponding stages of building assessment tools. Hence, there is currently no tool to empirically measure resilience in the various temporal stages and validate its implementation.

Before evaluating resilience implementation levels, it became essential to organise and visualise the various resilience enablers. A literature review in Study E (Paper V) identified that the IDEF0 functional modelling method (IEEE, 1998; Morgan and Stilwell, 1983) (Figure 4) was well-suited to structure and visualising the resilience enablers of a complex value chain's business processes. The study chose this method for the following reasons:

- It is a widely accepted method of modelling risk management and resilience.
- It allows a graphical depiction of the end-to-end processes in a value chain.

- Hotspots related to risks can be visualised and domino effects prevented.
- It allows easy comprehension and visibility for all stakeholders in the value chain.
- It allows rapid and easy process mapping.

The IDEF0 model used for structuring and visualising resilience enablers (Study E) was developed as a first step in the resilience assessment process. This model was then further developed into a resilience assessment tool (Study F) as the next step in resilience assessment. Additional details of the resilience assessment process can be found in Section 4.3.

To summarise, resilience assessment methods or tools should:

- Estimate resilience potential and its realisation (how it deals with risks) by developing resilience dynamic capabilities.
- Include the temporal phases of resilience.
- Be easily understood for self-assessment by practitioners.

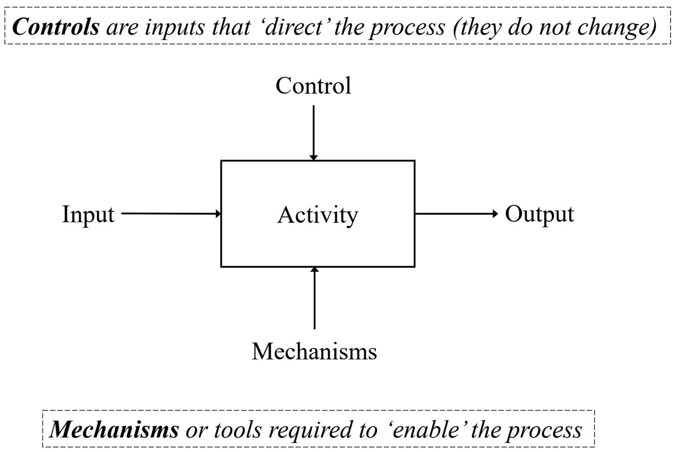

Figure 4. Top-level context diagram of an IDEF0 functional model proposed as a resilience assessment tool (From Study E, Paper V).

Studies E and F provided methods for visualising and assessing resilience and applied them to empirical cases for validation.

2.6 RESEARCH GAPS IDENTIFIED IN THE THESIS

After considering the theoretical background presented earlier and reviewing the studies conducted within this thesis, the identified research gaps (outlined below) will be the focal points of investigation in this thesis:

1. As previously described in Sections 2.2 and 2.3, risks and global sustainability issues that cause disruptions in manufacturing operations require a comprehensive understanding of resilience which could, in turn, impact sustainability. However, resilience and sustainability are multi-dimensional concepts with several underlying factors (and with interrelationships amongst those factors). There is no consensus in either the literature or practice as to how these concepts are related, especially in the manufacturing domain. A conceptualisation of these terms is an important first step before identifying the enablers and mechanisms to build manufacturing resilience.
2. There is no understanding of the building blocks (enablers) that can help build manufacturing resilience for sustainability. Previous literature describes enablers of

resilient manufacturing systems. These include open manufacturing that could benefit design-for-resilience (Kusiak, 2020), collaborative planning, information sharing, use of IT tools, process integration and leadership (Agarwal et al., 2020), change management process capabilities (Ates and Bititci, 2011) and internal, external and enabling factors (Gunasekaran et al., 2011). However, these are inadequate as some are capabilities or tools, while others are strategies or practices.

3. There is no structuring of the resilience enablers and how they are organised for building manufacturing resilience. Current models (Table 1 in Paper V) and SC mapping techniques (Mubarik et al., 2021) for building resilience are not adequate in understanding the categorisation and dependencies between enablers (a holistic view) for building manufacturing resilience.
4. No measurement tool encompasses the different temporal stages of resilience and the capabilities and practices that can guide manufacturing companies in assessing their resilience. Current tools (Table II in Paper VI) are either qualitative frameworks or quantitative metrics that may not easily be applied by manufacturing companies.

3

"It is not that there are the starry heavens above and the moral law within, as Kant would have it; rather, the true basis of your virtuous existence is the fact that the starry heavens are within you, and you are within them."
— Roy Bhaskar (1944-2014), The initiator of the Critical Realism philosophy

RESEARCH APPROACH

This chapter describes the author's philosophical and theoretical standpoint, which underpin the design and methods chosen to conduct the research.

OVERVIEW

The author has always been inspired by nature, particularly its resilience, but humans' interaction with nature and their overconsumption habits have led to its degradation. Given contemporary manufacturing companies' objectives of transforming digitally whilst pursuing sustainability, it became essential to explore strategies through which companies and their value chains could become more resilient at addressing sustainability challenges and thus help protect and preserve planet Earth.

A researcher's perception of the world can impact how they conduct research in an inquiring system (a researcher's efforts to study parts of reality (Törnebohm, 1976)). This perception, known as a 'researcher's paradigm' (Kuhn, 1962) is a set of shared ideals and beliefs (Guba and Lincoln, 1994) that characterise a researcher's efforts. These ideals then inform the methodological choices undertaken to carry out the research. Overall, a paradigm consists of the following attributes (Säfsten and Gustavsson, 2020): (i) world view, or how the nature of reality is viewed (ontology); (ii) how knowledge is generated (epistemology); (iii) the different norms that constitute good research; and (iv) ethical guidelines for conducting research. The author's own paradigm has been explained in Section 3.1

A methodological landscape (Figure 5) can help map out the reality that is to be studied and a perception of it using three levels (Säfsten and Gustavsson, 2020). The properties and nature of the studied phenomenon (within that part of reality for which we have accessible data and information) can be broken down into two types, qualitative and quantitative. Accordingly, different data collection and analysis techniques will need to be carried out (Level 1), via research methods (Level 2) that are governed by the various philosophy of science approaches (Level 3). Each of these levels is detailed in the following sections.

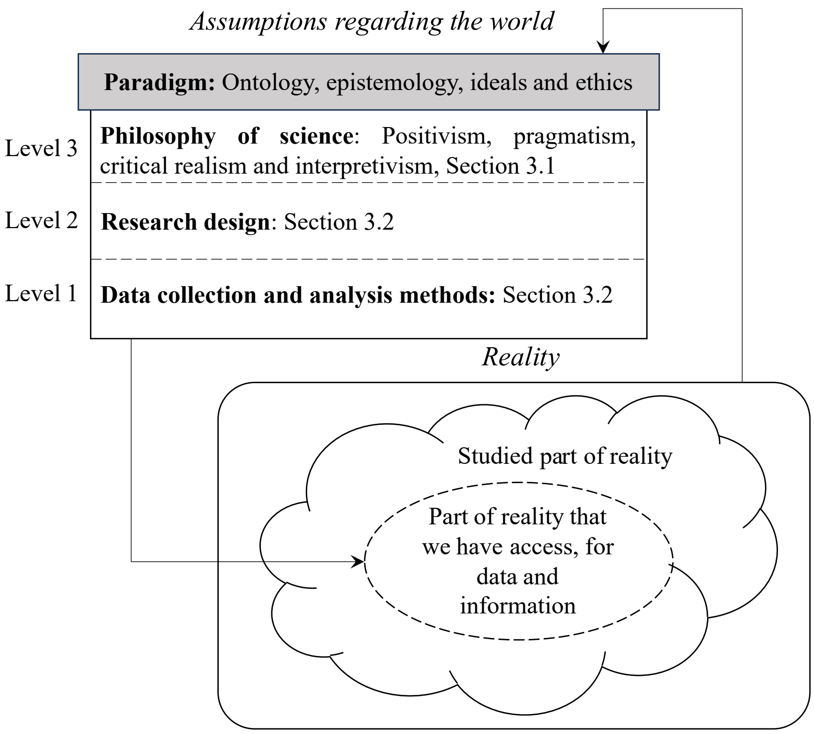

Figure 5. Methodological landscape [adapted from (Säfsten and Gustavsson, 2020)].

3.1 PHILOSOPHICAL FOUNDATION & THEORETICAL BACKGROUND

There are various philosophy of science approaches relating to the different aspects of a research paradigm. Positivism, interpretivism, critical realism and pragmatism are but a few. As a researcher dealing with different situations and cases in manufacturing companies, the author sometimes found herself at the crossroads between critical realism and pragmatism. In critical realism, reality is independent of the observer but socially constructed through, say, the language used by interviewees. The author used a multiple-case study methodology, emphasising interviews as a primary data source. Within this framework, she sought to uncover the subtleties and fundamental mechanisms governing the various cause-and-effect relationships of the constructs in her research, adopting a perspective aligned with critical realism.

In some studies, the author also used a pragmatic approach, in which an idea or theory is verified using practical activities and continuous knowledge generation as a tool to solve problems. The pragmatist perspective is a subject of debate, as some scholars contend that it may be an ad-hoc method of elucidating research methodology, perhaps lacking thorough pre-research design considerations. However, the 'learning-by-doing' expression, popularised by Dewey (1908) and which lies at the heart of the pragmatic view, is a sentiment that resonated strongly with the author, particularly in certain studies conducted within the thesis.

For the problems or research gaps addressed in this thesis (Section 2.7), the primary focus was, firstly, to understand the underlying cause-effect relationships between resilience and sustainability and how DCs could support the building of manufacturing resilience (Studies A, B and D). Here, a critical realist approach was useful. The pragmatist approach was useful when the utility or value of the practical activities was important in addressing the objectives of the thesis (Studies C, E and F). To summarise, the author has come to understand that maintaining a steadfast allegiance to a single scientific approach can be challenging. It is possible that a researcher may find themselves shifting between one or more approaches based on the specific case being studied.

Based on the main philosophy-of-science approach used in this thesis, the different aspects of the research paradigm are explained below.

3.1.1 Ontology

As much as the author would like to consider her world view on the nature of reality as 'objective', with (unchanged) reality always existing no matter who observes or perceives it (Säfsten and Gustavsson, 2020), in reality, it is difficult to adopt such a position. The author also takes a materialistic ontological position where reality exists *a priori*, after which consciousness is used to create something from it (Knowles, 2006).

3.1.2 Epistemology

Epistemology concerns the generation of knowledge with regard to its nature and relationship to reality (the ontological view). It can be divided into 'what' we can learn and 'how' we can learn it (Maynard, 2013). In terms of **what** we can learn, there are three broad viewpoints: *realism* (how things actually work in a single reality that is independent of the observer); *instrumentalism* (truth that is 'good enough' and should work in a given context); and *relativism* (reality can have multiple meanings, with findings that are independent of the observer). In the present research, meaning was continually derived from (participating) social actors in manufacturing companies (the reality) that are in a state of constant flux. Hence, the adoption of a relativist perspective naturally aligned with the author's aim of extracting meaningful insights from reality.

There are two extreme viewpoints as to **how** knowledge is generated (Säfsten and Gustavsson, 2020): *empiricism*, where the production of knowledge is based on experiences of the world and *rationalism*, where knowledge is created based on logic and discussions informed by reason. As an engineer, it is impossible to be a true empiricist or rationalist, as one may use both reasonings to derive knowledge. For instance, the knowledge the author gained was primarily through experiences of a reality consisting of manufacturing companies. The author drew upon this empirical knowledge and used reasoning to engage in discourse within the broader scientific community, deriving inferences grounded in her own logic and past experiences.

3.1.3 Scientific ideals and ethics

A researcher's scientific ideals are reflected in the methodological choices he or she makes (Säfsten and Gustavsson, 2020). The relationship between the rule (theory), observation (empirical data) and results (conclusions) can be made through inductive, deductive or abductive approaches (Bryman and Bell, 2015). Overall, the present thesis followed an abductive approach, whereby conclusions drawn from the results derived up until the author's licentiate degree were used to understand which theory (dynamic capabilities) may explain the research problem. The licentiate is the halfway mark of a PhD student's studies in Sweden. The author's licentiate thesis was entitled 'Sustainability transition of production systems in the digital era'(Chari, 2021). This rule was then confirmed through observational studies, using a multiple-case study approach (in which different tools and methods were tested and refined).

The thesis aimed to make general statements that are universally valid in a wider manufacturing context. This makes the research *nomothetic* (Åsberg et al., 2011), as opposed to *idiographic* research that characterises specific individuals or events. However, while the author aimed to derive generalisable and valid conclusions from her research, it is important to acknowledge that the outcomes may actually be more 'suggestive' than 'conclusive' (Crotty, 1998). The author conducted case study research (described in the following section) which is designed neither for statistical generalisation nor to be representative of a larger population. Rather, its purpose is to shed light on a broader issue or phenomenon.

In terms of the ethical guidelines followed in the thesis, certain dilemmas (such as confidentiality vs transparency, informed consent vs anonymity and conflict of interest) arose due to the pragmatic approach used in some studies. Here, the consequences of a decision had to be evaluated ethically, due to several possible courses of action for dealing with problematic situations (Säfsten and Gustavsson, 2020). These were meticulously considered in all the studies carried out in this thesis.

3.2 RESEARCH DESIGN

The findings of the author's licentiate in 2021 (Chari, 2021) revealed that resilience may be a key mechanism for enabling sustainability transitions in manufacturing. In essence, the author's research was motivated primarily by a focus on sustainability, while recognising the importance of resilience for companies. Although resilience was identified as an enabler (alongside dynamic capabilities and technologies from Industry 4.0), further research was required to understand which capabilities could build resilience and, hence, influence sustainability.

However, as the author's doctoral studies progressed, it became evident that resilience and sustainability are characterised by distinct objectives and foundational principles, in both theoretical frameworks and practical applications. This realisation prompted a systematic inquiry into the meaning of resilience in a manufacturing context, the constituents of the concept and their relationships with sustainability. The results of these findings aim to address Research Gap 1 (as described in Section 2.7) and answer RQ1.

Next, if manufacturing companies need to formally assess their resilience implementation, the elemental components or enablers of building manufacturing resilience had to be identified. The results of these findings aim to address Research Gap 2 (as described in Section 2.7) and answer RQ2. Following the elucidation of pivotal facilitators or building blocks of manufacturing resilience from RQ2, the enablers were structured into practical tools for assessing resilience, thereby addressing Research Gaps 3 and 4 (as described in Section 2.7) and helping answer RQ3. In other words, there was a lack of clarity as to how to implement resilience measures effectively. Another objective of formulating this RQ was to ensure the tools' pragmatic utility in real-world scenarios, whilst contributing substantively to the academic discourse of manufacturing resilience for sustainability.

This thesis primarily used a multiple-case study research methodology to answer the research questions outlined in Section 1.3. A case study is an empirical methodology that 'investigates a contemporary phenomenon ("the case") in depth and within its real-world context, especially when the boundaries between the phenomenon and context may not be clearly evident' (Yin, 2014 p. 15). A case may be defined 'as an instance of a class of events. The term 'class of events' refers to a phenomenon of scientific interest, such as revolutions, types of governmental regimes, kinds of economic systems, or personality types that the investigator chooses to study with the aim of developing theory (or "generic knowledge") regarding the causes of similarities and differences among instances (cases)' (George and Bennett, 2007 pp. 17-18). Hence, a case is a relatively bounded phenomenon within a study and has three fundamental aspects (Dumez, 2015) that must be addressed when defining a case study. This is shown in Table 5.

Table 5. Cases' descriptions (adapted from (Dumez, 2015)). Study D involved a systematic literature review and was not considered a 'case study'.

Study	What is my case a case of?	What is the stuff my case is made of?	What can my case/cases do?
A	Manufacturing supply chains.	Theory, eight individuals from manufacturing companies who shared their insights from a supply chain perspective.	Understand the relationship between resilience and sustainability.
B	Manufacturing companies.	Theory, data from the SCALER project, nine experts from academia and industry who shared their manufacturing expertise.	Generate insights on dynamic capabilities for circular and resilient supply chains.
C	Swedish Production2030 projects.	Manufacturing companies, academia.	Understand extent of sustainability and Industry 4.0 technology implementations and derive resilience factors
D	N/A.	N/A.	N/A.
E	Manufacturing supply chain.	Three manufacturing companies in a supply chain.	Visualise hotspots or dependencies of resilience enablers.
F	Manufacturing companies.	Six manufacturing companies in machine tool, aerospace, e-mobility and automotive domains; 11 experts from industry and academia.	Conceptualise manufacturing resilience and assess the current and future resilience implementation levels in manufacturing companies.

The selection of the case study research methodology over experimental, survey and historical research approaches stems from its unique capacity to explain intricate causal relationships in real-world settings beyond the scope of other methodologies. It excels in providing descriptive insights for evaluative purposes and shedding light on scenarios whose outcomes are not explicitly defined (Yin, 2014). The selection of multiple cases within the case study research methodology in this thesis served to enhance external validity and mitigate potential observer bias (Karlsson et al., 2016). For instance, Karlsson et al. (2016) explained that, although multiple cases may reduce the depth per case, the risks of conducting single cases could include misjudging information and exaggerating data. This could potentially be reduced when events and data are compared across cases.

A description of the data collection and analysis methods used in the different studies (or 'cases' within them) can be found in the following section, details of which are in the appended papers.

3.2.1 Relationship between the studies and research questions

During the author's PhD studies, six studies were conducted using different research designs, data collection and analysis procedures. Table 6 maps these studies (and corresponding appended papers) which helped in describing the problem to be solved (the aim of the study), whilst addressing the three research questions. The studies in the research relied on multiple sources of evidence, employing a triangulation approach to integrate data from each study. The data collection process incorporated a mixed-methods approach (including both quantitative and qualitative data) to enrich the conclusions (Creswell and Clark, 2007) and prevent common weaknesses from being shared (Jick, 1979).

Table 6. Methods adopted in the different papers *(QL: qualitative, QT: quantitative).*

Study	Paper	RQ1	RQ2	RQ3	Aim	Research Design	Data Collection	Data Analysis
A	I	x			Conceptualise manufacturing resilience and sustainability.	Case study.	Literature, interviews.	QL: Thematic coding of interviews and content analysis of literature.
B	II		x		Identify how DCs can enable circular and resilient SCs.	Literature review, case study.	Secondary data, literature, expert panel studies (semi-structured interviews).	QL: Content analysis of literature and secondary data, coding of interviews, proposition development.
C	III		x		Investigate extent of sustainability implementation in P2030's projects.	Case study.	Literature, questionnaire, interviews.	QL: Qualitative coding of interviews. QT: Descriptive statistics.
D	IV		x		Identify how digitalisation can enhance the environmental performance of manufacturing systems.	Systematic literature review.	Literature.	QL: Content analysis (studying academic discourse).
E	V		x	x	Demonstrate the use of IDEF0 models for digital platform implementation to build resilient	Case study.	Literature, workshops, I4.0 maturity assessments (which included	QL: IDEF0 modelling.

					and sustainable manufacturing SCs.		interviews).	
F	VI	x	x	x	Conceptualise manufacturing resilience and propose a resilience assessment tool.	Literature review, multiple-case study.	Literature, questionnaire, workshops, interviews	QT: CVI approach for development of measurement instrument QL: Qualitative coding of interviews.

The overall research process carried out in the thesis is shown in Figure 6. Each of the studies had various purposes and various ways of addressing the research questions (Karlsson et al., 2016).

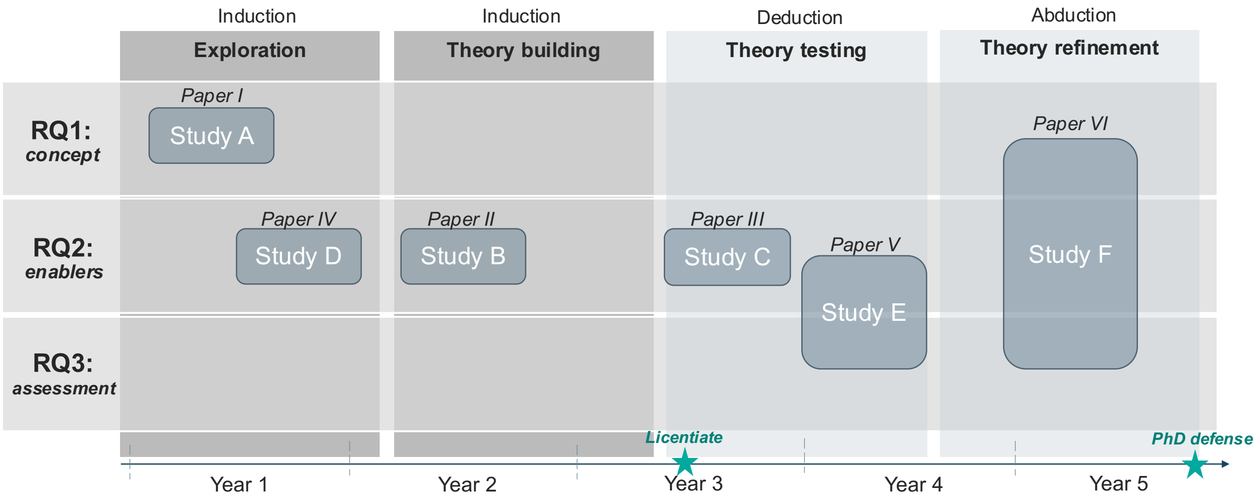

Figure 6. Research process.

Exploration was used in the early stages of the research, in which the state-of-the-art (SOTA) was studied, to develop ideas, define the research area and formulate research questions. An **inductive** approach was deemed best for this stage, as Study A was an in-depth case study and Study D involved a systematic literature review to justify the research topic.

Theory building helped identify the key constructs and variables of circular economy (sustainability) through dynamic capabilities and why the relationships existed (Study B). The case study method was useful for this, as the definitions and relationship between the different concepts (dynamic capabilities, circular economy/sustainability, Industry 4.0) were unclear. The study used an **inductive** approach, in which the lack of understanding between the concepts led to the development of propositions.

Theory testing was then conducted in the next phase using a **deductive** approach, in which the propositions developed in Study B were tested empirically in Studies C, E and F. When case studies are used in the theory testing phase, it is common to incorporate surveys (Studies C and F) and interviews (in all three studies), to ensure data triangulation (Karlsson et al., 2016).

The purpose of conducting *theory elaboration or refinement* through Study F was not to confirm the theory already tested in the previous phase but to elaborate upon its underlying logic and discover new phenomena (Dubois and Gadde, 2002). Here, an **abductive** approach was carried out in Study F where the logic of the microlevels of dynamic capabilities theory was reconciled with the temporal stages of resilience engineering (the 'contextual characteristic' as described by Ketokivi and Choi (2014)).

The process sequence between theory and empirical observations in the different research approaches used in the studies is shown in Figure 7.

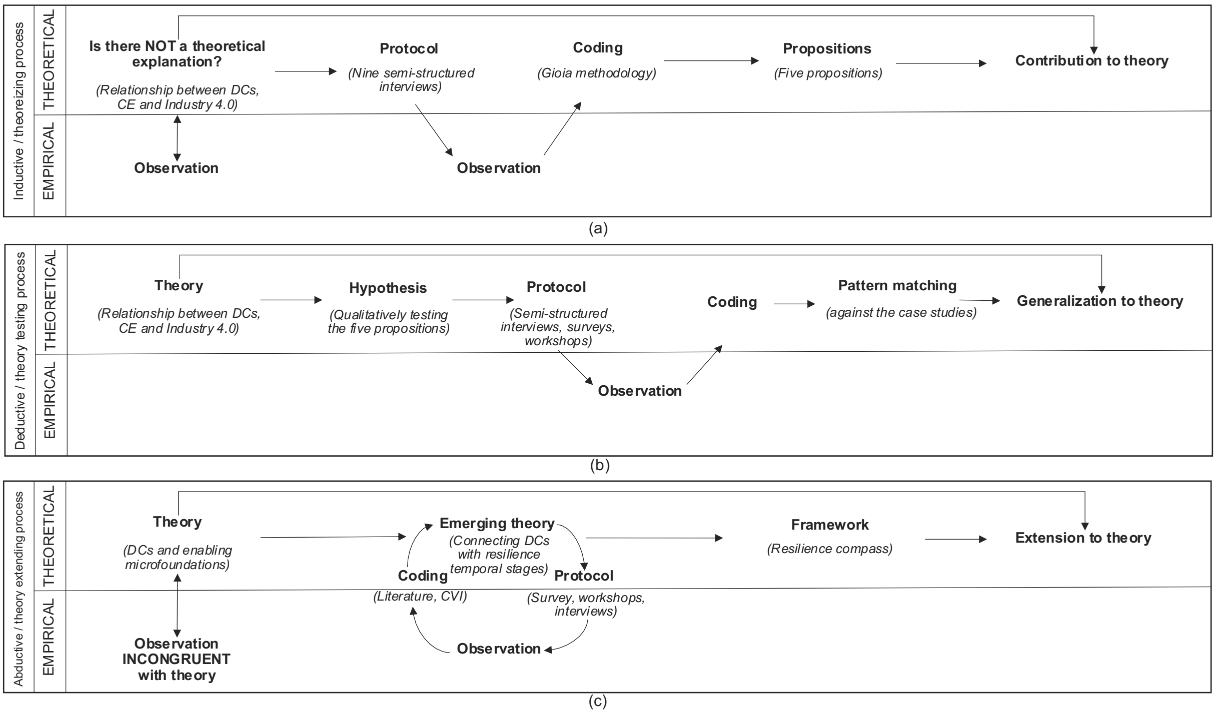

Figure 7. Process paths of the different research approaches carried out in the thesis (adapted from (Karlsson et al., 2016)). These are: (a) the inductive approach used in Studies A, B and D; (b) the deductive approach used in Studies C and E; and (c) the abductive approach used in Study F.

In the induction approach, it was observed that manufacturing companies are less resilient and sustainable. The synthesis of the results analysis in Studies A, B and D showed that manufacturing companies want to develop dynamic capabilities to become more resilient and sustainable. This allowed the identification of dynamic capabilities theory and the derivation of corresponding propositions that could support resilient and sustainable manufacturing. These propositions were then applied qualitatively in Studies C and E, with observations made that dynamic capabilities could offer a good solution for manufacturing companies to become more resilient and sustainable. Finally, Study F used the results of the previous deduction stage and checked the available literature on how dynamic capability microlevels were connected to resilience temporal stages. This abductive process led to the development of a resilience assessment tool in the form of a resilience compass. This was then used to analyse resilience implementation levels in six manufacturing companies.

The following paragraphs describe how the six studies answered the three research questions.

RQ1) Conceptualising resilience (Studies A and F)

Studies A and F provided the *conceptualisation* of resilience: the underlying terms that make up the larger resilience concept and the trade-offs between resilience and sustainability.

RQ2) Resilience enablers (Studies B-F)

Studies B-F helped answer RQ2. *Dynamic capabilities* theory was identified as the underlying theory that could support circular (sustainable) supply chains (Study B). At this point, five microfoundations of DCs were identified, as well as their relationships for developing circular and resilient SCs and five research propositions. Study E helped derive DCs to mitigate *risks* in a value chain and Study F developed a resilience assessment tool with 11 DCs for resilient manufacturing. Studies C and D described how *digitalisation* can support sustainability and Study E described how digitalisation can support manufacturing resilience.

RQ3) Assessment tools for building resilience (Studies E and F)

Studies E and F helped identify the assessment tools through which manufacturing resilience for sustainability can be built. These tools were based on the enabling factors from the answers to RQ2. As a first step, Study E provided an *IDEF0 modelling method* to structure and visualise the different resilience enablers in a manufacturing value chain. For the second step, a resilience assessment tool in the form of a *resilience compass* was developed in Study F. This was applied to six manufacturing companies to measure their resilience capability levels.

3.2.2 Methods used in the studies

The six studies conducted in this research followed different research methods to answer the RQs, based on the objectives of the studies. The following sections briefly describe the problem each study addresses, plus the data collection and analysis procedures carried out. A description of the 'case' in each of these studies was previously elucidated in Table 5.

Study A (Paper I): *Exploration*
Study A provided answers to RQ1. The research gap addressed here was the unexplored relationship between resilience and sustainability concepts in the manufacturing domain. This *explorative* study used a qualitative research design (Miles and Huberman, 1994) using a literature review and semi-structured interviews with eight supply chain experts. A specific string of keywords and screening criteria were used in the literature review. Details of the methods used in this study can be found in Appended Paper I.

Study B (Paper II): *Theory building*
Study B identified dynamic capabilities as the underlying theory for building manufacturing resilience for a circular economy (sustainability). The study was a part of the TRUST project (TRUST, 2018) and was conducted primarily for *theory-building.* Five microfoundations of DCs, their interrelatedness and five research propositions were identified. The interrelatedness of microfoundations, plus the derivation of propositions at the convergence of dynamic capabilities, resilience, sustainability and Industry 4.0 concepts indicated research gaps and paved the way for future work. The results of Study B helped in answering RQ2. A case study research method was used in the study which included data from a literature review, secondary data from the SCALER project and nine semi-structured interviews with experts. The interviewee quotes were coded according to a structuring methodology proposed by Gioia et al. (2012). Details of the methods used in this study can be found in Appended Paper II.

Study C (Paper III): *Theory testing*
Study C drew insights from survey data received from 78 projects within the Produktion2030 project (Produktion2030) to address RQ2. A study of specific Industry 4.0 technologies that can help derive resilience factors in manufacturing plus their implications for sustainability have not been elucidated clearly in either literature or practice; this study aimed to address these gaps. The study also helped to *test* whether some of the propositions derived from Study B were qualitatively valid. The study used a mixed-methods approach with a sequential explanatory

design. It used surveys and eight semi-structured interviews (which were thematically coded after transcription). Details of the methods used in this study can be found in Appended Paper III.

Study D (Paper IV): *Exploration*
The purpose of Study D was *explorative*, to identify a gap in the literature which would show how digitalisation can enhance the environmental performance of manufacturing systems. The study used a systematic literature review process, whereby a detailed analysis of 208 publications (empirical cases only) helped synthesise a research framework for digitalised sustainable manufacturing and produce eight research propositions. These results provided evidence to answer RQ2, as sustainable manufacturing (the main driver of the thesis) relies on digital technological advances, while current empirical studies are challenged when it concerns using environmental solutions. The list of keywords and screening criteria and other details of the methods used in the study can be found in Appended Paper IV.

Study E (Paper V): *Theory testing*
Study E *tested* some of the propositions derived from Study B. Although several models for building resilience do exist, a systems or holistic view of how resilience enablers are organised or mapped is missing. In this context, the use of the IDEF0 modelling approach was shown to identify (RQ2) and structure (RQ3) enablers for building resilience in a manufacturing value chain in Sweden, by using digital platforms.

The study was part of the Digitala Stambanan project (Digitala Stambanan, 2021) and used a case study methodology with three companies from a manufacturing value chain. Data was triangulated from three sources: (i) literature (to identify antecedents for digital platform implementation for resilient manufacturing and the different modelling approaches for resilience); (ii) four workshops (to identify the focus areas for resilient and sustainable manufacturing); and (iii) Industry 4.0 maturity assessments at each of the three companies (to understand digital maturity levels for digital platform implementation. Here, 30 people in total in the three companies were interviewed). Details of the methods used in this study can be found in Appended Paper V.

Study F (Paper VI): *Theory testing and refinement*
Study F was part of the RE4DY project (RE4DY, 2022) and used a four-stage mixed-methods approach in six manufacturing companies to develop and apply a measurement tool for resilience. The reason for using a mixed-methods approach was to reduce the subjective bias that exists at the convergence of sustainability and resilience fields.

The study was used to answer RQ1 (conceptualised the different resilience concepts), RQ2 (identified 11 resilience dynamic capabilities) and RQ3 (developed the resilience compass as an assessment tool to build manufacturing resilience). The practices and capabilities for resilience were derived from a comprehensive review of relevant literature. Subsequently, the survey results from 14 experts helped quantitatively evaluate the alignment of practices with the identified capabilities, by using the Content Validity Index (CVI) approach. This resulted in the development of a measurement tool known as the ‘resilience compass’.

The use of surveys complemented by interviews ensured triangulation and mitigated the limitations associated with relying solely on single methods (Jick, 1979). Furthermore, using the aforementioned resilience compass, two rounds of workshops and focused interviews were conducted at each of the six companies to assess the efficacy of resilience-building efforts. It is important to note that the objective of this study was to develop and validate a tool to measure/assess resilience in manufacturing companies without evaluating whether the tool actually improved the resilience of the companies. These results were documented in Paper VI, in which details of the methods used can be found.

4

"All this is a dream – still examine it with a few experiments."

– Michael Faraday

RESULTS

This chapter presents the results in relation to the three research questions of the thesis. The results stem from the six studies conducted during the research and the corresponding papers that emerged from the six studies (Papers I, II, III, IV, V and VI).

OVERVIEW

Table 7 provides an overview of the contributions of the research in relation to the appended papers in this thesis. RQ1 addresses how resilience and sustainability topics are conceptualised, RQ2 deals with the enabling factors that contribute to building resilience and RQ3 refers to the assessment tools for building resilience. A detailed description of the results is presented in the sections that follow.

Table 7. Contributions of the research in relation to the appended papers.

Contribution to RQ		
RQ1 (conceptualisation)	**RQ2** (enablers)	**RQ3** (assessment)
Paper I: Captures **relationships** -synergies, trade-offs and priorities between resilience and sustainability concepts. *Paper VI:* Unravels resilience terminologies for its **conceptualisation**.	*Paper II:* Derives **dynamic capabilities** as the underlying theory of **circular** manufacturing in an Industry 4.0 context. *Paper III:* Identifies **resilience** factors derived from **Industry 4.0** technology implementation and its **sustainability** implications. *Paper IV:* Recognises that **digitalisation** is a key enabler of establishing **sustainable** manufacturing. *Paper V:* Identifies antecedent resilience factors, such as **risks** and **dynamic capabilities** for digital platform implementation. *Paper VI:* Enables systemisation of criteria for resilience measurement, through the use of **dynamic capabilities**.	*Paper V:* Demonstrates the use of **IDEF0 functional modelling** method to structure and visualise interconnected antecedents for digital platform implementation. *Paper VI:* Develops a **resilience compass** for holistic measurement of resilience through **dynamic capabilities** during anticipation, coping and adaptation stages.

Three enablers were identified for building manufacturing resilience for sustainability: dynamic capabilities, risk management and digital technologies from Industry 4.0. These act as building blocks in the development of assessment tools for applying the resilience factors empirically in manufacturing companies and their supply chains. Two assessment methods were developed to structure and apply the resilience enablers empirically: an IDEF0 resilience modelling approach and a resilience compass. An overview of the results appears in Figure 8, each box of which is described in detail in the subsequent sections.

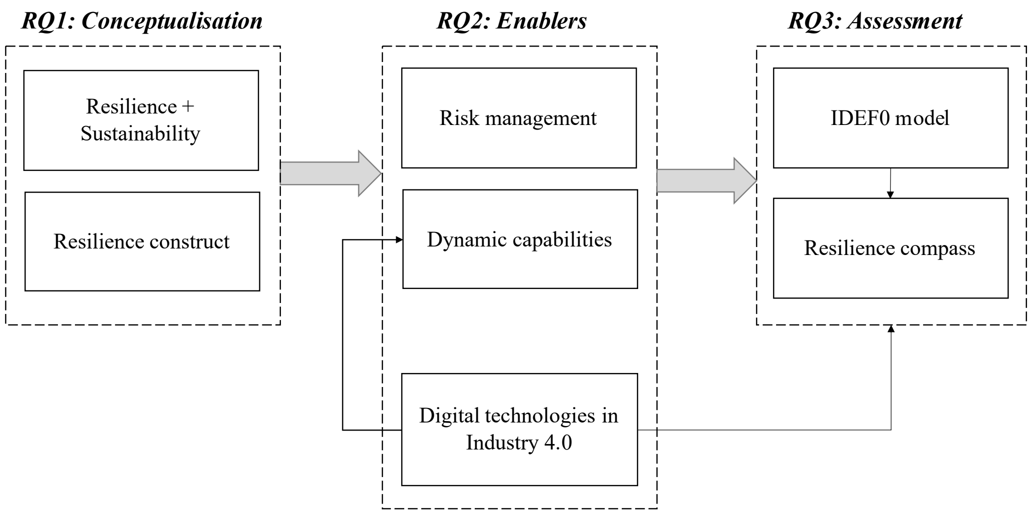

Figure 8. Overview of results of the thesis.

4.1 CONCEPTUALISING RESILIENCE

This section presents the results that answer RQ1: "How can manufacturing resilience for sustainability be conceptualised?" The results are supported by Papers I and VI (Studies A and F).

4.1.1 Conceptualisation (Studies A and F)

Manufacturing companies and their associated supply chains encounter a diverse array of challenges and their ensuing disruptions. Some of these challenges include sustainability imperatives, regulatory compliance, market dynamics and unforeseen contingencies. These unintended events call for the building of manufacturing 'resilience', a term that has been defined as the ability of firms to anticipate, cope with and continuously adapt to new and more desirable states (Paper VI). Such resilience strategies in the three stages must also be aligned with the triple bottom line of sustainability, if manufacturing companies are to address the challenges from the long-term threats of climate change (and the more immediate ones, such as scarcity of resources, increasing consumerism and the fast pace of technological revolutions (Paper I)).

As described in Chapter 2, resilience and sustainability are multi-dimensional topics with several underlying concepts. Furthermore, resilience and sustainability correlate in various ways. Understanding the core nature of resilience and sustainability – the possible synergies and conflicts (both convergent and divergent) – can make organisations redefine their strategies and operational practices to deal with unintended events. Study A was conducted to understand these relationships. Study F was conducted to further unravel the different underlying concepts that make up the resilience construct and study their relevance to the creation of resilience strategies. Further details of these results are discussed in Papers I and VI respectively, but the author provides a summary of the results in the following sections.

Relationships between resilience and sustainability (Studies A and F)

The key findings at the intersection of resilience and sustainability were:

1. Literature is primarily resilience-dominated: sustainability is considered a residual outcome of building resilience and was generally not considered as important as resilience.
2. Sustainability is primarily economic-centric: cost is still a major driver for businesses when it concerns connecting resilience factors with sustainability outcomes.
3. There are synergies between resilience dimensions and sustainability outcomes: one example found in the literature was that a resilient practice such as implementing information control systems enabled information-sharing with customers and suppliers thus minimising waste and the consumption of hazardous materials. Increased buffers could improve resilience and sustainability, as these resources reduce the uncertainty in an organisation and reduce transportation between supplier and producer.
4. Direct tensions/conflicts exist between resilient practices and sustainability of the supply chain: increased social and environmental sustainability could lead to increased cost and less robust supply chains. And although increased buffers could strengthen the resilience of the supply chain (as seen in point 3) it may also decrease the environmental sustainability due to increased waste.
5. Technology can be an enabler of the alignment between resilience and sustainability: it was seen in the literature that blockchain technologies can improve supply chain tracking, tracing, flexibility and overall responsiveness and enable circular economy

practices such as repair, refurbishment and reuse.

6. Resilience and sustainability are temporal in nature: empirically, resilience was considered a short-term strategy during disruptions at the operational level and a long-term strategy at the strategic and tactical levels. However, sustainability was mostly a long-term engagement with long-term targets.
7. In practice, sustainability has different prioritisations during disruptions: some companies did not focus on sustainability in times of crises, with one interviewee in Study A stating:

   > *"We have to focus first on maintaining our operation. This was the guideline or the direction during the Covid-19 outbreak, and from that aspect, we delayed all activities around sustainability and new product development in general"*

   The opposite was seen in another company in Study A:

   > *"We cannot see a resilient company able to handle external threats and challenges that is not sustainable overall. Companies that have an integrated sustainability approach in the whole business will have a significantly higher possibility of surviving in the next 10 years"*

8. The operationalisation of resilience and sustainability is siloed: resilience was based on economic incentives (and mainly prioritised) and handled by teams that were different from those that handled the social and environmental aspects.

Current supply chain efforts aimed at dealing with resilience and sustainability aspects showed that they are:

1. Internal or production-orientated: some companies implemented risk management (such as crisis management and associated task forces), circular economy efforts (such as take-back systems to limit constraints on primary raw material consumption) and optimisation of the production line, which led to both agile and lean outcomes.
2. Supplier-orientated: different sourcing strategies had positive and negative impacts on sustainability. Conversely, choosing sustainable suppliers affected the supply flexibility of some value chains.
3. Customer-orientated: most measures undertaken here positively impacted resilience and sustainability. Examples included remote diagnostics, remote maintenance and repair services, plus maintaining ownership of service operations/dealer network.
4. Value-chain orientated: the implementation of information-sharing and enterprise resource planning systems improved the collaboration, flexibility and visibility (amongst other things) to improve the sustainability and resilience of the entire value chain.

All six companies in Study F described the positive implications for social sustainability as a result of strengthening resilience capabilities. For instance, Company A from Study F mentioned that the practices implemented to build the 'security' DC are important, as they 'have a high impact at the social level considering the number of employees in the plant'. Another example cited by the company (for coping capabilities such as 'flexibility' and 'agility' and adaptation capabilities such as 'contingency planning') required rapid reaction to unpredictable changes which meant job stability: 'Any plan to keep production going upon disruptions means job stability'.

Other positive sustainability outcomes observed from building resilience:

- Circular economy mechanisms such as take-back systems and repair/remanufacturing helped build resilience; it limited the dependence on secondary materials whilst decreasing environmental impacts. Supplier-orientated efforts such as collaboration and continuous communication between manufacturer and supplier helped improve all aspects of the triple bottom line and increased the supply chain's resilience (Study A, Paper I).
- Agile practices can help manufacture products for CE. Developing proactive resilience capabilities (sensing stage) can accommodate CE practices, as opposed to being reactive or defensive. Leadership and strategy categories under the organisational capability microfoundation can form the basis of I4.0 technology implementation and derive CE benefits (Study B, Paper II).
- 65% of projects in Produktion2030 (Study C) adopted I4.0 technologies to derive sustainability benefits. In general, these technologies gave rise to more resource and energy-efficient operations, reduced production waste, produced zero defects, fostered safe and efficient cooperation in human-machine interactions, reduced the level of manual labour and physical stress due to automated material handling and so on. A detailed mapping of I4.0 opportunities for building industrial resilience for sustainability can be found in Paper III.
- Digital platforms allowed clear visualisation of the carbon footprint across all stakeholders in the value chain, thereby identifying critical hotspots. Thus, alternate suppliers and materials could be planned for waste and emission reduction (Study E, Paper V).
- The companies assessed in Study F had an overall positive outlook towards sustainability outcomes when it came to developing resilience capability. Some of the observed examples included: increased visibility capabilities leading to efficient resource consumption; increased redundancy capabilities leading to increased optimisation of processes; and more environmentally friendly transport.

Negative relationships between sustainability and resilience:

- Several trade-offs between resilience and sustainability were found in Study A: setting long-term sustainability goals and lean practices negatively impacted the flexibility and agility of some firms. Multiple sourcing negatively impacts the collaboration between suppliers, while choosing a sustainable supplier limits the flexibility of supply (more details are found in Paper I).
- Lack of redundancy in suppliers could give rise to an increase in scope 3 emissions due to the dependence on geographically dispersed suppliers (Study E, Paper V).
- Material redundancy could affect lean management and increase costs (Study E, Paper V). This was also seen in Study F, in which increased redundancy capabilities increased costs as more resources were used.

Unravelling resilience terminologies (Study F)

As described in Chapter 2 of this thesis, the field of resilience engineering – especially the supply chain literature – comprises several different terms including capabilities, strategies, actions, practices and sub-factors. Study F conducted a conceptualisation of the factors that make up the resilience concept. The outcomes of that study revealed that manufacturing resilience can be strengthened by developing dynamic capabilities by implementing organisational practices. These dynamic capabilities then occasion higher-level resilience strategies that need to be developed in temporal phases so that organisations can effectively prepare for, respond to and learn from disruptions (Figure 9). Accordingly, three temporal resilience stages of anticipation, coping and adaptation were identified, as well as 11 corresponding dynamic capability microfoundations (detailed in Section 4.2.2) and 54 resilience-building practices. The list of practices can be found in Paper VI.

The 11 dynamic capabilities were identified in the literature and underwent pilot tests with four experts. The development of the resilience measurement tool using the quantitative content validation index (CVI) approach gave insights into 54 specific resilience practices that must be implemented to build the dynamic capability microfoundations. These practices were identified using the literature and 14 experts. Additional details can be found in Paper VI.

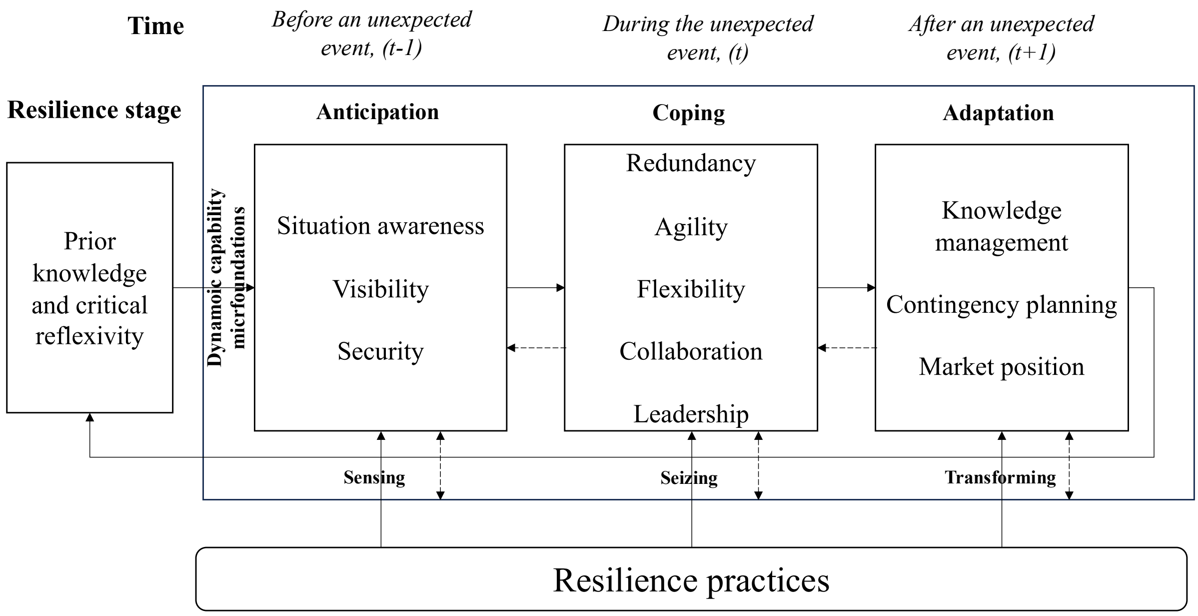

Figure 9. Resilience practices, capabilities and strategies according to the three temporal stages of resilience (from Study F, Paper VI).

4.1.2 Summary of aspects that help conceptualise resilience

In terms of conceptualisation, the intersection of resilience and sustainability was considered highly relevant both in the literature and from practice but was much less developed empirically. A convergence was seen on the conceptual and theoretical levels but was more fragmented in practice. The terms are often not understood, especially regarding operationalisation, with resilience seen to be operating in both short-term and long-term perspectives. However, sustainability was seen as a long-term engagement. Nevertheless, resilience is mostly prioritised in the short term, which inhibits long-term sustainable development. Resilience also comprises temporal stages: anticipation (before a disruption occurs, when manufacturing companies need to be reactive); coping (during disruptions, when companies are reactive); and adaptation (after disruptions, when companies learn and transform).

4.2 ENABLING RESILIENCE

This section presents the results that answer RQ2: "What enables manufacturing resilience for sustainability?" The results are supported by Papers II-VI (Studies B-F) and categorised into the following sections.

4.2.1 Risk management (Study E)

As described in Chapter 2, risk management is an integral part of building the resilience of manufacturing companies and their value chains. Risk management strategies reduce the probability or consequence of negative events from occurring because organisations can identify, assess, respond, mitigate and prioritise risks. However, this thesis focused on the first step of risk management, which is 'risk identification' – an enabler of building manufacturing resilience.

Risks must also be categorised in terms of their severity, frequency and impact (disruptions) to prevent a domino or ripple effect from occurring in supply chains (Study E, Paper V). Accordingly, 21 high-impact risks were identified in Study E, six of which were described in Paper V. One of these risks was visualised in an IDEF0 model (described in Section 4.3.1) to showcase the hotspots and possible domino effects in the supply chain if suitable capabilities and mitigation strategies were not developed. Risks/disruptions that cannot be contained within an organisation become risks/disruptions in the next dependent organisations in the value chain.

4.2.2 Dynamic capabilities (Studies B, E and F)

From Study B, it was identified that dynamic capabilities theory provided the underlying theoretical foundation for building circular supply chains. In turn, Studies E and F showed that dynamic capabilities could allow manufacturing companies to respond to risks and corresponding disruptions.

The literature review in Study B derived 18 categories of capabilities to promote circular economy efforts in supply chains. These were then validated empirically by industrial and academic experts to generate a dynamic capabilities model with five microfoundations of dynamic capabilities: communication, resources, organisation, technology and collaboration. These capabilities were categorised under the three dynamic capability microlevels of sense, seize and transform (Table 8).

Specifically, the findings of this study were a first step in identifying that resilience could be an important capability for developing circular or sustainable supply chains. Such a synthesis of dynamic capability microfoundations specifically for CE was not available in the literature, or in practice. In addition, the microfoundations were found to be interrelated, showing dependencies and requiring development in different stages. These results are documented in Paper II.

Table 8. The dynamic capabilities model for circular supply chains (Adapted from Study B, Paper II).

Dynamic capabilities model		**Micro-level capabilities**		
Dynamic capability microfoundations	**Categories**	**Sense**	**Seize**	**Transform**
Communication	Data	x		
	Knowledge	x		
Resources	Human		x	
	Physical		x	
Organisation	Operational strategy		x	
	Marketing strategy	x	x	
	Management strategy		x	
	Circular strategy		x	
	Leadership	x	x	
	Culture and mindset		x	
	Value capture	x	x	
	Production		x	
	Resilience		x	x

	Financial		x	
Technology	I4.0	x		x
	Innovation			x
Collaboration	Within company			x
	With external stakeholders			x

Additionally, six propositions were derived in Study B to examine the relationships between the concepts of dynamic capabilities, circular economy, Industry 4.0 technologies and resilience for sustainable supply chains. Of the six propositions derived in the study, four (Propositions 1-4) were evaluated in the studies conducted in the thesis. It is important to note that the propositions were not formally validated in the studies but created a direction for the work during the remainder of the author's PhD studies (following the licentiate). The propositions documented in Paper II are listed below:

Proposition 1: dynamic capabilities offer opportunities to generate sustainable competitive advantage in manufacturing supply chains.
Proposition 2: dynamic capabilities have a positive role in CE adoption in manufacturing supply chains.
Proposition 3: dynamic capabilities help build resilience for circular supply chains.
Proposition 4: I4.0 capabilities positively influence building dynamic capabilities which give rise to circular and resilient supply chains.
Proposition 5a: there is a cause-effect relationship between the development of CE capabilities on the resilience of manufacturing SCs.
Proposition 5b: there is a cause-effect relationship between the development of resilience capabilities on CE implementation efforts in manufacturing SCs.

A mapping of how the studies (conducted in this thesis) explored the six propositions appears in Table 9. Although propositions 1-4 were examined in detail in Study B, propositions 1 and 3 were also tested in Studies E and F. Proposition 4 was further strengthened through a systematic literature review in Study D, where digitalisation was identified as a key enabler of sustainable manufacturing. This proposition was also investigated empirically in Studies C, E and F. Study C specifically derived resilience factors by implementing Industry 4.0 technologies. These, in turn, can give rise to sustainability outcomes. Propositions 5a and 5b were not explored in the present thesis and require validation in future work. Although Study A investigated the relationship between resilience and sustainability, where some aspects of CE were embedded, Propositions 5a and 5b could not be fully validated (in the context of CE) in this thesis.

Table 9. Mapping of studies with the six research propositions identified in Study B.

Study	**Proposition**					
	1	2	3	4	5a	5b
A						
B	x	x	x	x		
C				x		
D				x		
E	x		x	x		
F	x		x	x		

Study E was conducted to build on the dynamic capabilities derived in Study B for resilient and sustainable supply chains. It addressed the challenges arising due to the various definitions and classifications of resilience capabilities in the literature. Specifically, the study identified the dynamic capabilities that manufacturing companies in a value chain need to develop so that appropriate mitigation strategies can be effectively deployed to respond to risks and disruptions. For some of the risks identified in the value chain in this study, different dynamic capabilities were categorised into the sense, seize and transform stages (Table 10).

A reflection on the dynamic capabilities identified in Study E was that they were not formulated as dynamic capability 'microfoundations' in Paper V. This is clarified in the title of Table 10. These dynamic capabilities were identified from previous work and in the literature. From the results of Study B (for circular or sustainable supply chains, Table 8) and Study E (for resilient manufacturing, Table 10), it can be observed that culture was categorised not only as a 'seize' capability but also as a 'sense' capability. That is, companies in Study E expressed that this may be an important capability to develop in the anticipation stage or 'sense' microlevel. The technology and information management systems capability that was categorised under the sense and transform levels in Study E, was categorised under the same microlevels as in Study B (where it was identified as 'I4.0').

Moreover, although a direct comparison of the dynamic capabilities from Study B and Study E cannot be made as the objectives were different, it can corroborate Proposition 3. That is, dynamic capabilities can help develop resilience which, in turn, could have sustainability implications (subsequently explored in Study F).

Table 10. Dynamic capability microfoundations required for mitigating risks in a value chain related to DC microlevels and resilience stages (adapted from Study E, Paper V).

Sense (Anticipation)	**Seize (Coping)**	**Transform (Adaptation)**
• Visibility. • Stakeholder involvement. • Technology and information management systems. • Culture. • Situation awareness. • Resource utilisation. • Redundancy.	• Stakeholder involvement. • Data sharing. • Dynamic collaboration. • Culture. • Communication and data sharing. • Resource utilisation. • Flexibility. • Technological innovation.	• Technology and information management systems. • Technological innovation.

Building on the findings of Study E, Study F identified 11 dynamic capability microfoundations and 54 practices for resilience from the literature and content validation from experts (Paper VI) (Table 11). This enabled a further conceptualisation of the resilience construct and its various underlying concepts. These were then categorised into the three resilience stages of anticipation, coping and adaptation. As mentioned before, these stages were found to be synonymous with the sense, seize and transform micro-levels of dynamic capabilities. It was also found that the dynamic capabilities could be categorised under more than one resilience stage. For instance, knowledge management could be an anticipatory capability during the pre-disruption stage in which simulation exercises, drills and overall risk awareness training could take place in the supply chain. The same capability could also occur in the post-disruption or adaptation stage where feedback, increasing innovation for contingency planning and business continuity, education and training and upskilling of workers could happen.

Redundancy was found to be a ‘sense’ capability in Study E, in which value chain companies stated that it was an important capability to develop and prepare for before disruptions took place. However, it was found to be a ‘seize’ capability in Study F, in which resources needed to be managed and deployed during disruptions.

Thus, placing the capabilities under strict categorisations is not simple. However, the categorisation of capabilities in the resilience compass (Section 4.3.2) gave an initial understanding of where capabilities could be placed, to then begin resilience implementation efforts.

Table 11. Stages and dynamic capabilities for resilience (adapted from Study F, Paper VI).

Resilience stage	Dynamic capability microfoundations
Anticipation (sensing)	Situation awareness
	Visibility
	Security
Coping (seizing)	Redundancy
	Agility
	Flexibility
	Collaboration
	Leadership
Adaptation (transformation)	Knowledge management
	Contingency planning
	Market position

4.2.3 Digitalisation in Industry 4.0 for resilient and sustainable manufacturing (Studies B-F)

Digitalisation was identified as a possible key factor for enabling sustainability efforts in manufacturing companies (Studies E and D) - the primary driver of this thesis. Digitalisation can systematically implement environmental solutions as part of the continuous improvement processes of companies (Study D), rather than as an add-on, ‘nice-to-have’ or a residual effect of building resilience (as observed in Study A). Studying the impact of Industry 4.0 technologies in depth was not the focus of the thesis. However, an understanding of their influence on building resilient and sustainable manufacturing was repeatedly found to be relevant. Hence, this thesis treats it as an important enabler.

A systematic literature review conducted in Study D revealed four research themes and eight propositions to align digitalisation and sustainability goals. The four themes were: digital environmental impact analysis; sustainable cyber-physical systems; digital knowledge platforms and communication solutions; and ethical data management and cybersecurity. The literature review in Study B (Paper II) indicated that Industry 4.0 technologies have tremendous potential for providing circular economy benefits. Study C mapped some of these opportunities and benefits from a sample of Swedish manufacturing companies in Produktion2030 projects. In particular, the technology enablers of Industry 4.0 provide opportunities for strengthening the resilience of manufacturing operations. This, in turn, could have sustainability and circular economy benefits (Paper III).

It was suggested that to generate sustainability, digital technologies must be integrated with established best practices (Study D) for resilience (Study F). This could be implemented through the following technologies (the highlighted parts relate to the opportunities of I4.0 technologies, the underlined parts to sustainability and the italicised parts to resilience efforts):

- Cyber-physical systems may enable (Papers III and IV):
    - factory **automation** and *coordination efforts between people and machines*.
    - a social perspective on automation which may, in turn, enable *flexibility*, workers' health and safety, wellbeing and socially inclusive environments.
- Digital platforms and communication solutions (Papers IV and V) can:
    - facilitate internal/external **communication and knowledge transfer** to support *collaboration*.
    - share **information** in a *timely* and sensible manner to harmonise sustainability and resilience efforts.
- Digital threads (Paper IV) can increase **data transparency** by *pushing information along the value chain* to identify trade-offs and rebound effects.
- Digital **maturity** (Paper V) and digital **literacy** (Paper IV) play important roles in productively exploiting Industry 4.0 technologies.
- Virtual Development tools, such as AR and VR, may lead to more *agile forms* of **data collection** and thus reduced scrap production and zero-defect production (Paper III).

With resilience considered a success factor in gaining competitive advantages in manufacturing and transitioning towards sustainability in a digital future, various opportunities were identified based on Industry 4.0-based enablers (Paper III). Efficiency, fast prototyping speeds and machine set-up, transparency and visibility in information flows, the ability to innovate through business models and enhanced collaboration with customers were some of the opportunities derived from the I4.0 technologies implemented in the various Produktion2030 projects whose members were interviewed in Study C. Specifically, these I4.0 opportunities were mapped to five resilience capabilities such as robustness, agility, resourcefulness, adaptability and flexibility (Paper III).

Specifically, some companies were able to operate more efficiently regarding resources, time and energy, something which was linked to the resilience capability of 'robustness'. The literature revealed that when considered together, robustness and resilience could help reduce the vulnerability of organisations (Colicchia et al., 2012). New, agile forms of data collection resulted in reduced waste; this was linked to the resilience capability of 'agility'. Increased visibility in production logistics was a direct result of transparent data and product information flows, giving rise to 'resourcefulness'. Simulation models and other virtual prototypes were used to assess the potential of business models such as product-service systems (PSS) which have been known to build the 'adaptability' of manufacturing companies. Lastly, IoT and CPS were found to improve the 'flexibility' of manufacturing, with faster machine set-ups, reduced machine downtimes and seamless adaptation to new circumstances. However, 'robustness' was later identified as a term that could not be categorised under the 'resilience' concept in Study F. Definitions of these different capabilities can be found in Chapter 2.

Study E (Paper V) analysed the antecedents to implementing a specific technology from the Industry 4.0 suite of technologies – multi-sided digital platforms (MSPs) – for resilient and sustainable value chains. The antecedents identified for resilience using MSPs were risk management and dynamic capabilities, the latter of which could help develop resilience strategies in the three temporal resilience stages (described in detail in Section 4.3). The challenges, requirements and opportunities of digital platforms to enable resilience in four focus areas of the value chain were also identified (Paper V). The four areas were: product data used by the customer; understanding customer requirements; data for predicting and securing delivery (delivery assurance); and visualisation of VC carbon footprint (green transition). The study also used the Industry 4.0 Maturity Index to assess the value chain's maturity for digital platform implementation.

Study F recognised the potential of Industry 4.0 technology enablers for resilient and sustainable manufacturing. Some examples of the technologies mentioned in the six manufacturing companies as potential future enablers of the three resilience stages were:

Anticipation: to enable anticipatory capabilities, Company C mentioned platform initiatives such as IDSA (RAMI4.0) and BDVA, as well as digital continuity, AI forecasts, digital product passports for upcoming CE legislative restrictions, e-procurement, connected factories, data sharing in data markets (for, say, Catena-X in the automotive sector), technologies that support energy-efficient data processing and storing. Company D wants to implement ERP software extensions to monitor supply chain activities, internal data spaces to make employees aware of upcoming initiatives and production data lakes with IoT devices sending data directly from the machines.

Company E highlighted the challenges of automating various aspects of 'situation awareness' owing to diverse communication channels across different countries. Nonetheless, the company expressed its desire to implement automated internal and external data analysis systems. These systems aim to facilitate the early detection of changes and leverage AI to scan market trends, thus enhancing the optimisation of planning activities. Company F currently uses AI market intelligence software for anticipating major disruptions in the market, plus state-of-the-art cyber security tools.

Coping: in this context, Company B plans to use AI/ML for visual inspection to support the training of junior inspectors for quality improvement. Company C mentioned that, for their suppliers to keep relevant items in stock for fast deliveries, connected factories and supply chain platforms like Catena-X and knowledge-based simulation platforms will be helpful. This is because, from an economic point of view, it is important to reduce KPIs like stock and storage; Company D has open data sharing of their highly flexible production environment, as well as data storage of historical production data so that different customers can optimise new products. Company F mentioned that digital platform eco-system implementations are ongoing for this resilience stage and that SAP coordination is in place with key suppliers.

Adaptation: AI for the workforce (AI assistants for resource management with multi-disciplinary optimisations) was a technology echoed by multiple companies in the study. Company C is currently in the process of developing AI tools for PLM, ERP, machine data, semantic and management purposes. Taskforces have been formed to thoroughly investigate the potential benefits of these tools, with particular emphasis on enhancing knowledge management and upskilling the workforce during this resilience stage. Connected factories, dataspaces and e-procurement are also being developed for zero-defect manufacturing supply chains, as they are currently not agile and flexible enough to react to market needs and changes. Company F currently has ongoing predictive maintenance developments at product level. There is much manual work and cabling involved in their processes, making it difficult to be agile. When asked whether there would be more automated assembly in the future, Company F said no, as high throughputs were not expected.

Overall, a strong culture for dealing with failures is most important; who or what failed is not as important as understanding why it did and how to prevent further failures (Company C). Company E mentioned that it was unnecessary to automate simply for the sake of automating resilience practices; some employees did not have day-to-day access to computers and current manual scenario planning processes have worked well so far.

4.2.4 Summary of resilience enablers

Based on the gaps found in the literature (Chapter 2), three enablers were identified as relevant building blocks for manufacturing resilience: risk management, dynamic capabilities and digital technologies in I4.0. Companies that shift their focus by adopting more environmentally friendly technologies in I4.0 can develop the necessary capabilities and be better able to manage disruptions than their competitors.

4.3 ASSESSING RESILIENCE

This section presents the results that answer RQ3: "How can manufacturing resilience be assessed?" The results are supported by Papers V and VI (Studies E and F). Two methods of assessing resilience were identified: the IDEF0 functional modelling method and the resilience compass.

4.3.1 The IDEF0 method: organising resilience enablers (Study E)

Data collection and the structuring of risks and capabilities have important roles to play before a resilience assessment is carried out. This generates an understanding of how to assess resilience and provides a holistic picture of resilience to manufacturing companies. Although not a mandatory step in the resilience assessment process, the IDEF0 method can be used as a first step in the assessment process to capture, understand and visually represent flows within an end-to-end supply chain. It was chosen from a plethora of tools available in the literature to model business processes (described in Section 2.6), with the key purpose being to showcase the interrelatedness and dependencies of resilience-enabling factors. The IDEF0 is a standardised way of modelling large and complex systems and can handle multi-level complexities.

Figure 10 shows the three enablers identified in this thesis for building resilience. Risks and corresponding disruptions identified in Study E were visualised as 'controlling' factors. In other words, they are aspects that influence or impact upon building manufacturing resilience. Dynamic capabilities were visualised as the mechanisms that help deal with the risks (Study E) by developing mitigation strategies in the three resilience stages of anticipation, coping and adaptation (Study F). Moreover, Industry 4.0 technologies could help develop resilience dynamic capabilities (Studies E and F).

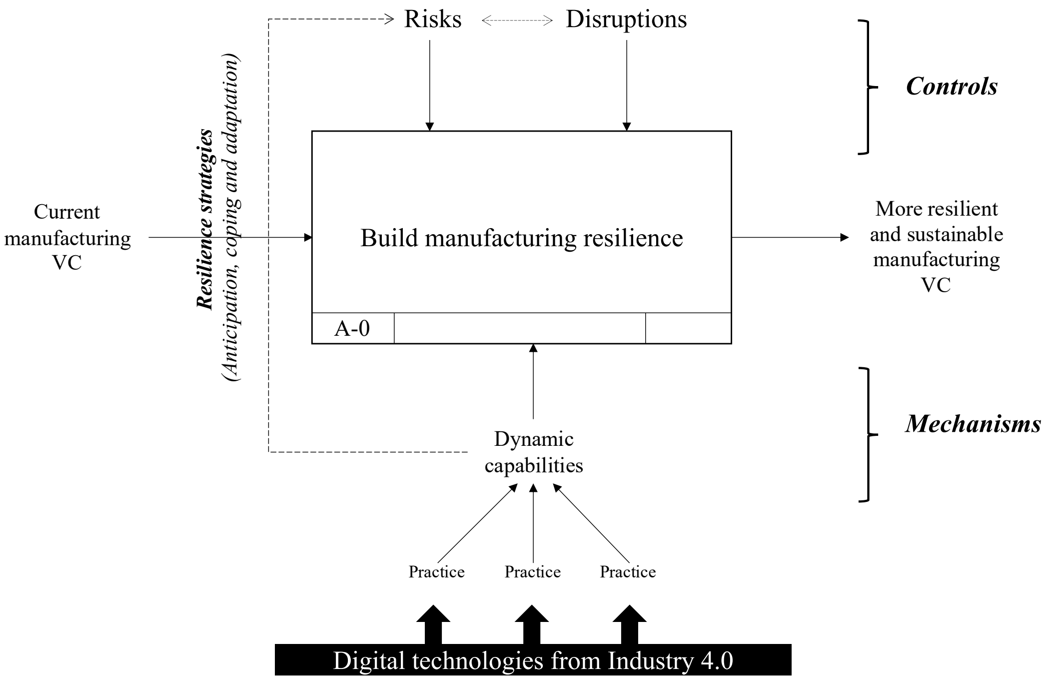

Figure 10. Mapping resilience enablers using the IDEF0 functional modelling method.

The IDEF0 model was applied in each of the three manufacturing companies in Study E, to understand risk-related hotspots which might arise if corresponding resilience capabilities are not developed to mitigate them. As described in Section 4.2.1, one of the high impact high probability (HIHP) risks that impacted the value chain was visualised using the IDEF0 model to observe its interrelatedness to the entire value chain's capacity to manage the risk (Figure 11). Additional details can be found in Paper V.

The structuring and visualisation of resilience enablers helped in creating the resilience assessment tool in Study F, called the 'resilience compass' (the different practices bundled as dynamic capabilities). The dynamic capabilities further helped develop resilience strategies in the three temporal resilience stages. These stages could be related to the dynamic capability microlevels of sense, seize and transform.

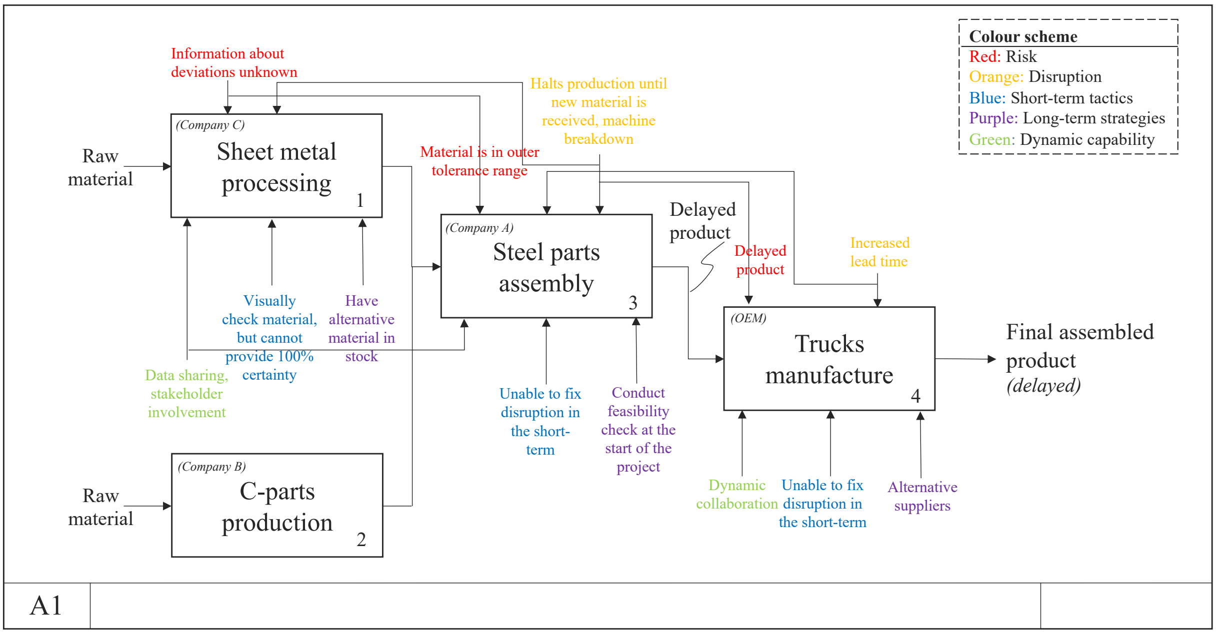

Figure 11. IDEF0 model depicting the interrelated risks, disruptions and capabilities of a value chain (Study E, Paper V).

4.3.2 The resilience compass: assessment tool (Study F)

The resilience compass was created as a navigational tool to provide companies with a sense of direction on where they currently are in their resilience capability implementations and where they would like to be (their future state) (Study F). Any lack of capability implementation will become evident when companies are faced with risks and how to deal with them.

The resilience compass was based on a refined measurement instrument developed in Study F. It comprised three temporal resilience stages, 11 dynamic capabilities (Figure 12) and 54 practices for resilience. Figure 12 shows an assessment conducted at one of the six manufacturing companies assessed in Study F. The difference in capability implementation levels was marked with coloured dots representing how far along the companies were in their current and future states (more details on the methods and results can be found in Paper VI).

For instance, the company assessed (shown in Figure 12) had sufficient leadership and security capabilities. In general, resilience did not require the highest capability level of 5 and the company was satisfied with its resilience capability implementation level regarding market position and redundancy capabilities. For instance, for its type of manufacturing domain (the logistics department of an automotive assembly plant) the company chose a level of 3 for some practices under 'situation awareness' reasoning that: *"Logistics scenario planning is done extensively, mainly to accommodate fluctuations in production/client demand or occasional volume fluctuations"*.

This company wanted to improve its visibility, agility, flexibility, collaboration and contingency planning capabilities (as indicated by the red dot, which showed a difference of >1 between the current and future states). However, this was not always feasible for its organisation. For the flexibility levels chosen for its current state, the interviewee at the company stated: "*Such strategies are highly unlikely to happen. Usually, when there are spikes in demand, the main focus is on helping the supplier meet that demand by investing/adapting or optimising its production process*" and "*The automotive industry is extremely rigid and* *complex. This is highly unlikely to be carried out in the short-to-medium term*" In general, the company mentioned that its cultural mindset was the most important aspect to consider as it impacts upon the decisions taken for capability implementations aimed at mitigating risks.

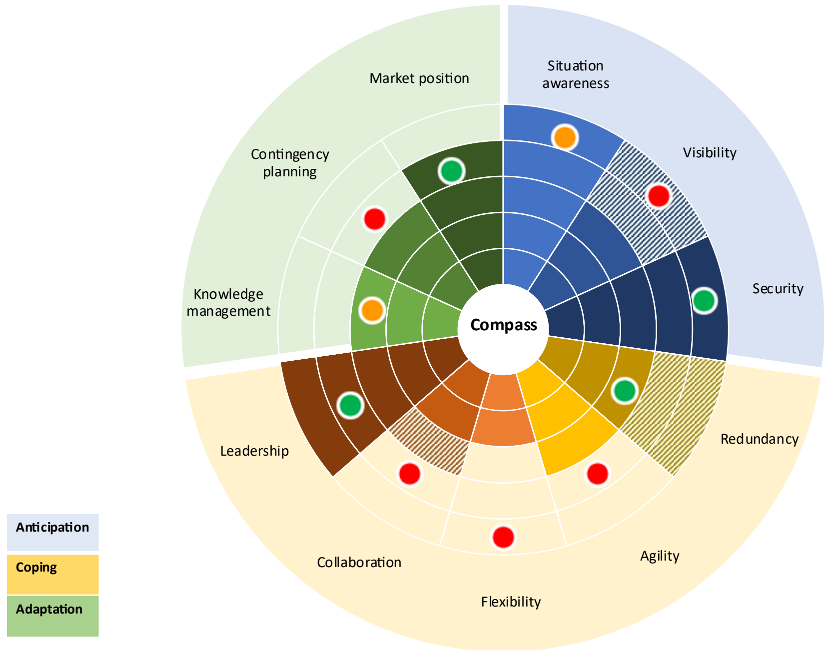

Figure 12. The resilience compass (Study F, Paper VI).

Additional results from the resilience compass assessments have been documented in Paper VI of Study F and further details can be found in deliverable D2.3 of the RE4DY project (RE4DY, 2022) which will be available after May 2024.

4.4 SYNTHESIS OF RESULTS

This section synthesises and presents the results of the different studies that addressed RQ1, RQ2 and RQ3.

The aims of the thesis were: (i) to determine the constituent relationships between manufacturing resilience and sustainability, plus their underlying concepts (RQ1); (ii) to identify manufacturing resilience enablers (RQ2); and (iii) to investigate the methods that might help manufacturing companies and their value chains assess the resilience of their operations (RQ3). This section describes the contribution of the results to the three research questions.

RQ 1) How can manufacturing resilience for sustainability be conceptualised?

Before the manufacturing resilience enablers were identified, it became imperative to first understand resilience and sustainability concepts. Although several studies tried to understand these terms separately and some jointly (Chapter 2), there seemed to be a lack of understanding of what these terms mean or clear empirical derivations, especially in a manufacturing context. Study A was carried out to clarify the relationships between these concepts, after the author's licentiate when the research topic was further narrowed down. Study F was carried out to further understand the underlying factors of the resilience concept, plus the sustainability implications of building resilience. Figure 13 summarises the findings of Studies A and F on conceptualising resilience and sustainability.

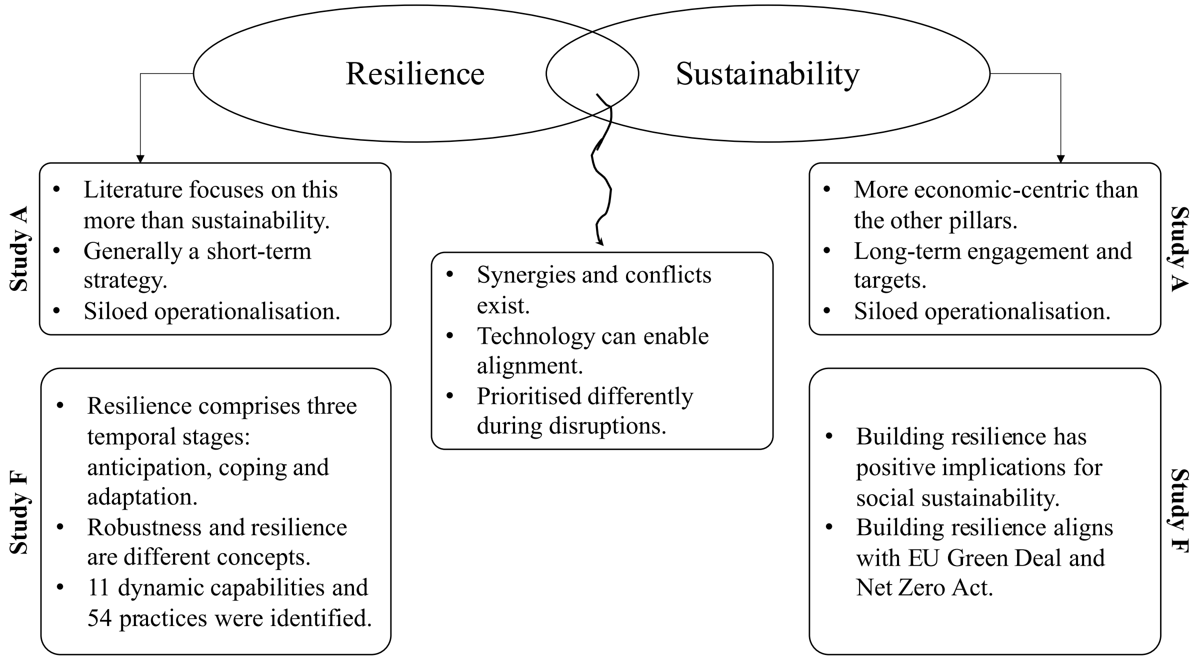

Figure 13. Conceptualisation of resilience and sustainability.

RQ 2) What enables manufacturing resilience for sustainability?

As described in Section 4.2, three enablers were identified as important factors in building manufacturing resilience for sustainability: risk management, dynamic capabilities and technologies from Industry 4.0. These formed the building blocks that helped formalise resilience assessment methods to help answer RQ3.

Study B showed that dynamic capabilities theory forms a strong theoretical underpinning in deriving resilient and sustainable manufacturing value chains. The dynamic capabilities derived in Study B were further developed in Studies E and F for building resilience. Study E empirically evaluated the dynamic capabilities required to deal with risks, on both the manufacturing companies' level and the value chain level. This study showed that the lack of resilience dynamic capabilities for dealing with risks in one company can have a domino or ripple effect in companies further down the value chain. Study F described resilience dynamic capabilities in three temporal stages of resilience: anticipation (before a disruption occurs), coping (during a disruption) and adaptation (after a disruption occurs). Study E identified risks that impact manufacturing supply chains and the resilience capabilities for dealing with them.

Digital technologies in Industry 4.0 offer capabilities for building resilience that could have positive sustainability implications. Specifically, Study D identified that digitalisation is a key enabler of sustainable manufacturing – the key driver of this thesis. Study C then empirically identified the resilience factors derived from Industry 4.0 technology implementations and generated sustainability outcomes. Study E used a specific instantiation of Industry 4.0 technologies (digital platforms) for collaboration in value chains by structuring and visualising resilience enablers, such as risks and dynamic capabilities.

RQ 3) How can manufacturing resilience be assessed?

The IDEF0 modelling technique was used to structure and visualise the resilience enablers: risks and corresponding disruptions as controls and dynamic capabilities as the mechanisms (Study E, Paper V) for resilient and sustainable manufacturing companies and value chains. Examining this step was crucial, not only at the manufacturing firm level but also in investigating their interconnectedness with stakeholders throughout the value chain, so that corresponding domino effects can be accounted for.

Based on an understanding of how the resilience enablers were structured (from Study E), the resilience compass was created (Study F) to understand how manufacturing companies can implement resilience dynamic capabilities. This measurement tool can help companies assess their resilience capability implementation levels (resilience potential) and understand how to utilise them effectively in mitigating risks and corresponding disruptions.

5

"It's not what you look at that matters, it's what you see."

– Henry David Thoreau, American philosopher

DISCUSSION

This chapter discusses the results in relation to previous work and how they contribute to building manufacturing resilience. It also describes the theoretical and practical contributions of the research with a view to future work.

OVERVIEW

This chapter discusses the research according to the following six criteria:

- The thesis in relation to previous work and addressing research gaps.
- The extent to which the results contribute towards building scientific knowledge (theoretical contribution) and can support industrial practitioners (practical contribution), plus avenues for future work.
- Quality of the research.
- Research limitations.
- Did the author carry out her mission successfully?

5.1 HOW DOES THE THESIS RELATE TO PREVIOUS WORK?

This section describes how the thesis relates to previous work and its significant contributions with regard to addressing the research gaps identified in Section 2.7.

Missing a conceptualisation between resilience and sustainability

As sustainability constituted the primary driver of this thesis, it was only logical to explore the connections between building resilience and its implications for sustainability. The literature states that resilience can help manufacturing companies derive sustainability benefits (Gunasekaran et al., 2011; Rajesh, 2019) and that the converse relationship is seen, with circular economy practices (Le et al., 2023) and business models (Lopes de Sousa Jabbour et al., 2023) giving rise to resilience.

Hence, this thesis studied the conceptualisation of synergies, trade-offs and an understanding of manufacturing supply chain efforts towards achieving the convergence of resilience and sustainability. However, no strong connection between the two concepts could be made in any of the studies. This could be because the conceptualisation of resilience in manufacturing is still in a nascent stage, with a connection to sustainability even newer. This contribution does not completely fill Research Gap 1 (identified in Section 2.7) and is, therefore, a partial or secondary contribution.

Missing building blocks for manufacturing resilience

The supply chain resilience literature (SCRES) (Christopher and Peck, 2004; Sheffi and Rice, 2005) elucidates the fact that risks and risk management play an important role (Negri et al., 2021). Although risk management was considered an important enabler of building manufacturing resilience, risk identification (which has been considered in this thesis) may not always be possible or sufficient (Fiksel et al., 2015). Hence, resilience should be a separate and complementary process to traditional risk management approaches (Fiksel et al., 2015; Pettit et al., 2013).

Risk management (particularly risk identification), dynamic capabilities and digital technologies from Industry 4.0 were identified as the building blocks or enablers of manufacturing resilience for sustainability. These enablers were then organised using an IDEF0 model to identify interrelatedness and dependencies. Risk management was seen as a controlling factor and dynamic capabilities as the mechanism for dealing with risks.

Industry 4.0 offers opportunities for sustainable manufacturing (Stock and Seliger, 2016), but may not always align with sustainability (Machado et al., 2020). This thesis has offered insights into how digitalisation can support the implementation of environmental solutions in manufacturing and empirically studied how some technologies from Industry 4.0 can give rise to sustainability outcomes (benefits as well as drawbacks).

Missing a resilience measurement method

Although Fiksel (2017) provided a systems approach to understanding resilience, the proposed models lacked an understanding of the concrete practices and capabilities involved (in temporal stages) in implementing and achieving resilient manufacturing. This thesis has identified dynamic capabilities (or dynamic capability microfoundations) in the three microlevels of sensing, seizing and transforming (Teece, 2007) which may be synonymous with the three resilience stages of anticipation, coping and adaptation. Teece (2007) further explicated how the 'microfoundations' which are unique to manufacturing firms can make them competitive. These were also found to be interconnected and interdependent. Hence, 'resilience' is not just a buzzword but can be developed by implementing concrete practices for resilience (54 such practices were identified). These, in turn, can help build dynamic capabilities (11 such capabilities were identified) in the three temporal stages of resilience. Resilience must be 'designed' into the system, not just by coping with stressors but by also proactively planning and learning from them.

The terminology of 'resilience factors' used in Study C (at the beginning of the author's PhD studies) developed into 'dynamic capabilities' for manufacturing resilience as the PhD studies progressed (Studies E and F). Based on this, a measurement tool known as the 'resilience compass' which incorporates the various temporal stages of resilience was developed. This compass can guide manufacturing companies in assessing their resilience.

The contributions of this thesis in relation to the research gaps highlighted in Section 2.7 are summarised in Table 12 (research gaps 2-4). As mentioned before, the first gap could not be addressed fully because the convergence of the sustainability and manufacturing resilience fields is not mature yet.

Table 12. Contributions to the research gaps that were addressed.

<table>
<tr><th>Research gaps</th><th>Contributions</th><th>Aspects that could not be addressed and which require further work</th></tr>
<tr><td>2. Missing building blocks for manufacturing resilience.</td><td rowspan="2">Theoretical: conceptualisation of manufacturing resilience and identifying the building blocks. These are: dynamic capabilities, risk management and the influence of digital technologies in Industry 4.0.</td><td rowspan="2">Not all stages of risk management were explored and only the first step of risk identification was studied. Specific digital technologies in Industry 4.0 and their impact on sustainability were not studied in detail (except for one instantiation of digital platforms in Study E). Several other enablers for building resilience might be included and these need to be explored in future work.</td></tr>
<tr><td>3. Missing a systemic view of resilience.</td></tr>
<tr><td>4. Missing a resilience measurement method.</td><td>Practical: a measurement tool called a 'resilience compass' with 54 resilience practices connected to 11 DCs and three temporal resilience stages.</td><td>Resilience potential will need to be tested in the form of capability deployment and how it can help mitigate risks. However, this was not addressed in this thesis and needs to be explored in future work.</td></tr>
</table>

5.2 RESEARCH CONTRIBUTION

5.2.1 Theoretical contribution

Fisher and Aguinis (2017 p. 439) discussed how theory advancement can occur through empirical conceptualisations that include 'contrasting, specifying or structuring theoretical constructs and relations' and stated specific tactics for theory elaboration. This thesis has made a theoretical contribution by conceptualising manufacturing resilience. This was done by explaining the relationships between existing concepts linked to resilience (the practices, capabilities and temporal stages of resilience) and creating propositions (linking CE, resilience, dynamic capabilities and Industry 4.0). The thesis has contributed to both supply chain resilience and dynamic capabilities fields, establishing a connection between them. This link allowed observations across various contexts to be contrasted.

The supply chain management literature considers resilience to be a fundamental capability of organisations (Brusset and Teller, 2017; Rice and Caniato, 2003). However, this relationship is contested (Bhamra et al., 2011). This thesis has used the dynamic capabilities theory from a different domain (the strategy management field) in the current disciplinary context of production and operations management. This theory has helped identify new relationships and the sequential interactions between capabilities for sustainability and resilience. This is aligned with the author's critical realism research philosophy, which was used to try and understand underlying causal relationships.

The dynamic capabilities theory also helped in better understanding the convergence of resilience, CE and I4.0 concepts and elucidated how dynamic capabilities may help mitigate risks in manufacturing companies and their supply chains. This thesis has helped break down the broader manufacturing resilience construct into dynamic capabilities and practices (construct splitting). This formed the theoretical basis for framing the resilience measurement tool (a practical contribution of the thesis which is described in the next section).

5.2.2 Practical contribution

Further building upon the author's philosophical framework, the multidimensionality of the various DC microfoundations may help industrial practitioners map out which DCs could support their transition to circular supply chains and thus outperform their competitors. Another practical contribution involved a method that helped organise and visualise enablers and the development of a measurement tool for building manufacturing resilience. These are readily comprehensible to practitioners. Some advantages of implementing resilience enablers include: the visualisation of dependencies between risks in a supply chain; the elucidation of specific resilience practices to develop resilience dynamic capabilities; real-time data availability due to the instantiation of resilience factors on digital platforms; and an opportunity to initiate manufacturing improvement discussions from a strategic perspective.

Based on these findings, the following recommendations are proposed to industrial practitioners:

1. Since it was recognised that resilience and sustainability implementations can be siloed, the author recommends that planning teams that include stakeholders from different functional areas in manufacturing companies might be built to manage vulnerabilities, respond to disruptions and understand their implications for sustainability.

2. Several Industry 4.0 technologies were identified which can help build resilience for sustainability. However, manufacturing companies should recognise the trade-offs between such opportunities, the development of resilience capabilities in different temporal resilience phases, the corresponding sustainability benefits and how they align with companies' core business strategies.

3. Develop and implement dynamic capabilities as part of an organisation's need to strengthen different resilience capabilities and understand their implications for sustainability.

4. Develop a proactive risk management culture (as also proposed by Parker and Ameen (2018) and Chowdhury et al. (2019)) in the SC. This includes: (i) risk identification; (ii) specifying the source of the risk (internal, external in the SC or outside the SC); (iii) severity of risk; (iv) frequency of risk; (v) corresponding disruption; and (vi) identifying and implementing appropriate risk mitigation strategies. The resilience compass proposed in this thesis provides an opportunity to develop resilience capabilities, a tool which may be useful in managing risks and building overall manufacturing and supply chain resilience.

5.2.3 Future work

The cases in this research were limited to manufacturing companies in the EU. Future work will need to explore other geographical locations where stressors, resilience conceptualisations and applications may vary. Hence, domain, company size, location and cultural mindset are important aspects that could impact resilience and sustainability investment and which require further investigation. Although a variety of manufacturing domains (machine tool, steel, automotive, aerospace and so on) was analysed in the various studies, this may not have been sufficient to ensure generalisability of the findings. Since the current research context was within discrete manufacturing, future testing will also need to be conducted in the process industry. Industries may adopt the recommended microfoundations of dynamic capabilities (Studies B and E) and encompassing resilience practices (Study F). However, these were not meant to be comprehensive and leave room in which to conduct future research.

5.3 RESEARCH QUALITY

5.3.1 Relevance

Tracy and Hinrichs (2017) provide eight 'big tent' criteria for assessing qualitative research. They argue that high-quality qualitative research should encompass the following aspects: (1) worthy topic; (2) rich rigour; (3) sincerity; (4) credibility; (5) resonance; (6) significant contribution; (7) ethics; and (8) meaningful coherence. Many of these criteria are described in this section and the two that follow.

In terms of the relevance of this thesis: the next five to ten years are crucial for manufacturing companies, especially in the EU because of the sustainability regulations in the Green Deal aimed at driving decarbonisation efforts (halving emissions by 2030 and reaching net zero by 2050 (European Commission, 2019)). There is also the push for a 'sustainable, human-centric and resilient European Industry', as proposed in the Industry 5.0 approach (European Commission, 2021). This aims for a new triple bottom line (Elkington, 2018) built upon the sustainability model previously proposed by Elkington (1998). The findings of the studies in this thesis show that the convergence of topics considered – resilience, sustainability and increased availability of data in Industry 4.0 – are relevant, urgent and opportune for further research.

5.3.2 Validity

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

Triangulation of data: all six studies used multiple data sources; something which can enhance the accuracy of the findings (construct validity (Yin, 2014)). The various forms of evidence used were interviews, focus groups, workshops, secondary data, literature and questionnaires. For instance, the literature helped identify the practices and capabilities for resilience in Study F, with the surveys further validating the relationships between the capabilities and practices.
Member checking: thematised data from the interviews (Studies A, B, C, E and F) was sent back to the participants and experts to confirm accuracy, omit sensitive information and enable further additions (construct validity (Yin, 2014)).
Data saturation: the information collected from the eight interviewees in Study A, the nine experts in Study B, the eight follow-up interviews in Study C and the 11 survey participants in Study F did not reveal any new information. Thus, no further participants were contacted for additional data collection.
Internal validity: Yin (2014) describes pattern matching (whether an empirical pattern and a predicted pattern are similar) as a sufficient criterion for checking the internal validity of an explanatory study. The empirical findings of the experts in Study B were thematised and categorised under the dynamic capability microlevels of sense, seize and transform. These three microlevels were also found to be synonymous with the three temporal stages of resilience in Study F.

5.3.3 Generalisability (external validity)

As described in Section 3.1, the author aimed for the research findings to be generalisable in different contexts within discrete manufacturing. However, Crotty (1998) describes how, in reality, these outcomes may be more suggestive than conclusive. Generalisation techniques typically seek to establish a broad applicability of findings. However, Creswell (2003) noted that these methods have restricted utility in qualitative research. In qualitative studies, the emphasis is often on developing descriptions or themes tailored to specific contexts (Onwuegbuzie and Leech, 2009) and the pursuit of generalisability may be secondary to the contextual relevance of qualitative findings or 'particularity' (Miles and Huberman, 1994). Given the qualitative nature of the research carried out in this thesis, generalisability needs to be considered in this manner. In this context, analytic generalisations or case-case transfer of findings were used when concepts were related to each other and to theory.

Themes and underlying relationships between concepts were derived in Studies A, B and F at the convergence of resilience, sustainability, dynamic capabilities and Industry 4.0. Studies A, B, E and F used smaller samples, diverse cases and specific manufacturing contexts and it is difficult to claim generalisability of the findings of these studies. For the resilience temporal stages that were identified in Study F, all stages need to be considered if manufacturing companies want to build their resilience (a generalisable aspect of this research). However, not all the practices and capabilities may be necessary to be resilient (and they may not also be generalisable for all manufacturing sectors).

5.3.4 Reliability

The following methods were carried out to check whether the findings of the different studies were **consistent**:

Absence of errors: 'Otter.ai' (Otter Voice Notes, 2020) (AI software for transcribing audio files) and Microsoft SharePoint's transcription software were used to transcribe interviewee data in Studies A, B, C and F. 'NVivo' (Hutchison et al., 2010), a qualitative data analysis tool, was also used to thematise and store data from Studies B and D and manually edit the data.

Cross-checking results: the coding exercises conducted in Studies A, B and D were documented and shared with co-authors on a regular basis to ensure qualitative reliability of the findings. For instance, in Study B, CE implementation capabilities were first identified from the literature. Expert validation helped thematise the findings into the different dynamic capability microlevels of sense, seize and transform.
Repeatability: The research protocols used in these studies were clearly documented, in replicable fashion, using 'thick descriptions' (Lincoln and Guba, 1985), thus maintaining a transparent chain of evidence (Yin, 2014).

5.4 RESEARCH LIMITATIONS

The dynamic capabilities identified in Studies B, E and F were not tested for uniqueness. That is, if they were effective in fostering competitiveness in the companies. For manufacturing, it was more relevant to establish the connection between dynamic capabilities and the practices within resilience engineering.

The convergence of Industry 4.0 technologies, resilience and sustainability topics could not be investigated in depth in the studies, perhaps due to the novelty of this convergence. For instance, Study C could only identify the relationship between Industry 4.0 implementation and sustainability with an initial understanding of resilience-building factors. Moreover, although the companies in Study F described some Industry 4.0 technologies and their influence on building resilience, they did not have enough knowledge of how these technologies could impact sustainability. This requires further research.

Although the intention from the outset of the author's research was to study the sustainability implications of building resilience through the different cases, it was observed that the reality did not completely match this expectation. Study A's findings revealed that the relationship of sustainability with resilience is not well understood. Research into digital platforms for improving resilience is a fairly recent development, especially from an empirical perspective and the impact of such efforts on sustainability is even newer. Although the digital platform described in Study E enabled CO_2 visualisation of the end-to-end supply chain, it was not enough to substantiate the correlation between resilience and sustainability. The manufacturing companies who used the resilience assessment tool in Study F were asked to evaluate resilience implementation efforts on sustainability dimensions. Despite some insights being gained, they were insufficient to make a strong connection between resilience and sustainability.

5.5 MISSION (IM)POSSIBLE?

Going back to the 'vision' described at the beginning of this thesis (achieving long-term manufacturing resilience for sustainability in manufacturing companies and their supply chains), the author reflected on her 'mission', which was to provide companies with useful tools to apply in strengthening their resilience and which would have positive sustainability implications. So, was she able to realise her vision through this mission, during the course of her PhD studies?

The results derived from the thesis can support manufacturing companies and their supply chains in understanding resilience and being aware that developing resilience capabilities can also have sustainability implications. Resilience can be a source of competitive advantage rather than just being used for risk management measures (Klibi et al., 2010). This can prompt companies to start developing resilience thinking and the necessary capabilities for resilience reinforcement across the three temporal resilience stages.

Manufacturing companies should focus on their observable and controllable systems (Ivanov, 2023), embedding resilience as part of their business-as-usual operations. Being proactive to issues that go beyond current requirements can equip companies to respond effectively and adapt to future disruptions, including those stemming from unforeseen risks.

Despite ambiguity as to the meaning of resilience, sustainability and Industry 4.0, their overall concepts and underlying relationships, manufacturing companies are on the right track in embracing them and being willing to make the right efforts to improve their manufacturing performance whilst contributing to sustainability outcomes.

6

"Perfection is not attainable. But if we chase perfection, we can catch excellence."

– Vince Lombardi (1913–1970)

CONCLUSIONS

This chapter presents the conclusions of the thesis.

Manufacturing companies are presently grappling with high levels of uncertainty due to shifts in the geopolitical landscape, dependencies on critical resources, the emergence of new pandemic variants and the impact of climate change, to name just a few risks. In response, these companies need to find new ways of operating which are more sustainable. They also need to address disruptions to bolster their overall 'resilience'. Thus, to ensure that manufacturing companies can operate sustainably in dynamically changing environments, this thesis has contributed to conceptualising manufacturing resilience; its overarching terms and its relationship to sustainability. Resilience was recognised as a multidimensional concept comprising diverse phenomena and consisting of three temporal stages of anticipation, coping and adaptation.

Three enabling factors of manufacturing resilience were identified: (i) *dynamic capabilities* as the foundational pillars of an organisation's resilience when faced with risks and corresponding disruptions; (ii) the augmentation of proactive *risk management* methods (specifically risk identification) with resilience thinking; and (iii) enhanced data and information-sharing capabilities resulting (amongst other opportunities) from the adoption of *Industry 4.0 technologies*.

Moreover, the resilience enablers were *structured* using a resilience model based on the IDEF0 approach (which explained the dependencies and relationships between the enablers) as a first step in the resilience assessment process. A resilience measurement tool (in the form of a *resilience compass*) was then developed and subjected to empirical testing as a second step in resilience assessment. Some of the expected impacts generated from using the tool were: risk and disruption mitigation; a systemic understanding of resilience concepts; and the linking of such concepts to the generation of sustainability outcomes (the key driver of this thesis). However, complementary and unexpected results in terms of 'value' to the company were also found, such as: market differentiation; the ability to innovate and develop new sustainable business models; improvement in product quality; and organisational stability due to confidence from stakeholders and customers.

When taken together, the conceptualisation, enablers and assessment tools can ensure that manufacturing companies have sufficient buffers or safety mechanisms as prerequisites for achieving sustainability and making them less vulnerable to disruption. These may lead to lower costs, higher performance and innovative value propositions to set them apart from their competitors.

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