TRANSITION TOWARDS SUPPLY CHAIN 4.0

INTERWEAVING A TECHNOLOGICAL PERSPECTIVE – INSIGHTS FROM TURKEY AND BEYOND

FAKHREDDIN FAKHRAI RAD

SÖDERTÖRN DOCTORAL DISSERTATIONS

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Research Area: Politics, Economy and the Organisation of Society
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The Library
SE-141 89 Huddinge

www.sh.se/publications

Cover design: Jonathan Robson
Graphic form: Per Lindblom & Jonathan Robson

Printed by E-print, Stockholm 2024

Södertörn Doctoral Dissertations 232
ISSN 1652–7399

ISBN 978-91-89504-88-2 (print)
ISBN 978-91-89504-89-9 (digital)

Abstract

Supply Chain 4.0 represents a technological transformation in the way that supply chains work, extending the application of Industry 4.0 technologies from manufacturing and other advanced technologies into upstream and downstream processes. Despite the increasing global interest in this domain, the successful transition to Supply Chain 4.0 remains limited in practice, with existing literature highlighting its fragmented and under-conceptualized status.

Adopting a strategic management approach to supply chains, this thesis amalgamates dynamic capabilities theory with the business-technology alignment concept, drawing from the domains of Information Technology Management and Information Systems, complemented by the integration of the multi-level perspective derived from transition literature, to underpin the thesis framework. This framework is then enriched by identifying the trio of benefits, challenges, and critical factors associated with the transition to Supply Chain 4.0, thereby contributing to advancing the knowledge frontiers within the domain of Supply Chain 4.0.

This multi-method thesis uncovers the trio at two distinct levels: the technology level and the general Supply Chain 4.0 level. Twelve technologies closely associated with Supply Chain 4.0 are identified at the technology level, and the trio is analyzed in relation to each of these technologies. At the general level, the trio is examined in relation to Supply Chain 4.0 as a holistic concept. Insights derived from both these levels significantly enrich the thesis framework, offering valuable implications for the transition to Supply Chain 4.0.

At the technology level, the findings of this thesis unveil the trio of benefits, challenges, and critical factors in relation to the following twelve technologies: Internet of Things; artificial intelligence; cloud computing; blockchain; big data technologies; augmented reality; automation; robotics; additive manufacturing; simulation; Internet of People, and semantic technologies. At the general level, the trio of benefits, challenges and critical factors is identified as follows: benefits include supply chain transparency, enhanced decision-making, supply chain integration, and supply chain process optimization. Challenges encompass high costs, the scarcity of requisite skillsets, security and privacy concerns, infrastructure development complexities, intricacies of coordination in Supply Chain 4.0, and inherent complexities within the technologies themselves. Identification of critical factors at the general level is rooted in business-technology alignment, further divided into three alignment aspects: critical factors for Regime-to-Niche alignment, critical factors for Niche-to-Regime alignment, and critical factors for both Regime and Niche alignment. Critical factors related to Regime-to-Niche alignment involve supply chain process reengineering, data management, and management commitment. Critical factors concerning Niche-to-Regime alignment include an understanding of the Regime's context by technological solution provider, customization of technological design and solutions, and technological maintenance. Critical factors pertinent to both Regime and Niche alignment encompass providing requisite skillsets and knowledge, financial planning

and investment strategy, data privacy and security considerations, technological infrastructure development and interoperability, and supply chain collaboration. This thesis reveals that the Niche-Regime partnership is characterized by technological complementarity, symbiotic alignment, and finite establishments subject to change with the ever-evolving technological landscape. Ultimately, the trio is further expounded in relation to Turkey, where empirical investigations focus on Regime's supply chains.

Keywords: Supply Chain 4.0, technology, benefits, challenges, critical factors, dynamic capabilities, business-technology alignment, multi-level perspective, Turkey

Sammanfattning (Summary in Swedish)

Titel: *Övergång till Supply Chain 4.0: Integration av ett teknologiskt perspektiv – Insikter från Turkiet*

Supply Chain 4.0 representerar en teknologisk transformation av försörjningskedjor, som integrerar Industry 4.0-teknologier, i såväl uppströms- som nedströmsprocesser. Trots ökat globalt intresse är den framgångsrika övergången till Supply Chain 4.0 relativt avgränsad.

Genom att tillämpa ett strategiskt ledarskapsperspektiv på leverantörskedjor så kombinerar denna avhandling dynamisk kapacitetsteori med konceptet för affärstekniksanpassning och informationssystem. Avhandlingen försöker identifiera fördelar, utmaningar och kritiska faktorer associerade med övergången till Supply Chain 4.0, vilket ska bidra till att utveckla kunskapsfronten inom området.

Avhandlingen använder en flermetodsansats för att undersöka en trio av fördelar, utmaningar och kritiska faktorer på två nivåer: teknologinivå och allmän Supply Chain 4.0-nivå. Tolv teknologier relaterade till Supply Chain 4.0 identifieras och analyseras.

På teknologinivå belyses fördelar, utmaningar och kritiska faktorer för följande tolv teknologier: Internet of Things, artificiell intelligens, molntjänster, blockchain, big data, augmented reality, automation, robotik, additiv tillverkning, simulering, Internet of People och semantiska teknologier.

På allmän nivå inkluderar fördelarna transparens i försörjningskedjan, förbättrat beslutsfattande, integration och sist men inte minst optimering av processer i försörjningskedjan. Bland utmaningar omfattas höga kostnader, brist på nödvändiga färdigheter, säkerhets- och integritetsfrågor, infrastrukturutveckling, teknologi- och koordinationskomplexitet.

Vidare i avhandlingen indelas kritiska faktorer på allmän nivå i tre aspekter: Regim-till-nisch-anpassning, nisch-till-regim-anpassning och anpassning för både regim och nisch. Avhandlingen visar närmare att nisch-regim-partnerskap präglas av teknologisk kompletterande och symbiotisk anpassning, med ett ständigt utvecklande teknologiskt landskap. Slutligen utvidgas trion till ny kontext nämligen Turkiet, där empiriska undersökningar fokuserar på försörjningskedjor.

Nyckelord: Supply Chain 4.0, teknologi, fördelar, utmaningar, kritiska faktorer, dynamisk kapacitet, affärstekniksanpassning, flernivåperspektiv, Turkiet

Acknowledgement

Completing this PhD thesis would not have been possible without the invaluable support and encouragement of many individuals.

First and foremost, I want to express my deepest gratitude to my family, especially my parents, wife, and sister. Your unwavering love, patience, and understanding provided a constant source of strength throughout this journey. I dedicate this thesis to my child, whose innocent smile brought me so much joy.

My supervisors, Pejvak Oghazi, Koteshwar Chirumalla, and Christina Papadopoulou, thank you for your unwavering guidance and support. Pejvak, I am particularly indebted to you for your constant encouragement and mentorship throughout my PhD journey. Your vast knowledge and experience proved invaluable in navigating research challenges and kept me motivated throughout. I learned a lot from you. I will never forget all you have done for me. Koteshwar, I extend my deepest gratitude to you for your exceptional guidance during the development of my thesis. Your constructive feedback ensured the clarity and rigor of my research. Christina, I am grateful for your invaluable comments, especially regarding developing the Kappa. Your insightful suggestions strengthened the quality of my work. To all three of you, thank you for believing in my potential and pushing me to achieve my best. Your dedication to my academic progress is deeply appreciated.

My sincere thanks extend to Sweden and Södertörn University, particularly the School of Social Sciences and Business Studies department. I am also appreciative of the support from the Centre for Baltic and East European Studies (CBEES) at Södertörn University and The Foundation for Baltic and East European Studies (*Östersjöstiftelsen*), whose funding made this PhD project possible. I am grateful to the Södertörn library staff and the thesis proofreader for their contributions to the publication of this thesis. I also thank the Director(s) of Studies, the Research Officer, and the HR generalists in the School of Social Sciences at Södertörn University for their administrative support.

I would like to express my gratitude to all the authors who participated in the development of articles that involved me. I am especially grateful to Darek Haftor, who played a significant role in fostering my understanding of research development. Your insights were crucial in shaping my research approach.

I also want to acknowledge the insightful comments and questions from all the opponents at my PhD seminars and the jury at my PhD defense. The feedback provided by individuals at courses, seminars, workshops, and conferences enriched my understanding of the research and my topic. I am particularly thankful to the

green readers who generously allocated time to review my work at the final stage. Their constructive suggestions were invaluable in revising my thesis.

I am grateful to all the participants in the case study and everyone who facilitated my fieldwork. Your willingness to share your experiences and insights was instrumental in shaping this research.

Finally, I want to thank my friends for their companionship and support. Their encouragement during challenging times and shared celebrations during milestones kept me motivated.

Fakhreddin
Stockholm, 2024

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List of abbreviations

AI	(artificial intelligence)
AM	(additive manufacturing)
API	(Application Programming Interface)
AR	(augmented reality)
AU	(automation)
BC	(blockchain)
BCU	(blockchain user)
BDTs	(big data technologies)
BEES	(The Foundation for Baltic and East European Studies)
BSP	(Business Source Premier)
CC	(cloud computing)
Cobots	(collaborative robots)
CPS	(cyber-physical system)
ERP	(Enterprise Resource Planning)
GSCF	(Global Supply Chain Forum)
IaaS	(Infrastructure as a Service)
IIoT	(Industrial IoT)
IoP	(Internet of People)
IoT	(Internet of Things)
KPIs	(key performance indicators)
KVKK: Kanunen Kişisel Verilerin Korunması Kanunu	(Personal Data Protection Law)
MBV	(market-based view)
MLP	(multi-level perspective)
M2M	(machine-to-machine)
NDA	(non-disclosure agreement)
OECD	(Organisation for Economic Co-operation and Development)
PaaS	(Platform as a Service)
PwC	(PricewaterhouseCoopers)
RBV	(resource-based view)
RFID	(radio frequency identification)
ROI	(return on investment)
RO	(robotics)
RQs	(research questions)

SaaS	(Software as a Service)
SCOR	(Supply-Chain Operations Reference model)
SCP	(Structure-Conduct-Performance)
SI	(simulation)
SM	(smart machines)
ST	(semantic technologies)
TCO	(Total Cost of Ownership)
TOE	(Technology-Organization-Environment)
WoS	(Web of Science)
WWW	(World Wide Web)
3DP	(three-dimensional printing)

List of papers

Paper 1
Rad, F. F., Oghazi, P., Palmié, M., Chirumalla, K., Pashkevich, N., Patel, P. C., & Sattari, S. (2022). Industry 4.0 and supply chain performance: A systematic literature review of the benefits, challenges, and critical success factors of 11 core technologies. *Industrial Marketing Management*, *105*, 268–293.

Paper 2
Oghazi, P., Rad, F. F., Karlsson, S., & Haftor, D. (2018). RFID and ERP systems in supply chain management. *European Journal of Management and Business Economics*, *27*(2), 171–182.

Paper 3
Rad, F. F. (2021). From Far East to Baltic Sea: Impact of Quantum Computers on Supply Chain Users of Blockchain. *International Journal of Enterprise Information Systems (IJEIS)*, *17*(4), 85–97.

Paper 4
Title: Adoption of AI Based Order Picking in a Warehouse in Turkey: Benefits, Challenges and Critical Success Factors. Authors: Fakhrai Rad, Fakhreddin; Oghazi, Pejvak; İzmir, Onur; Kordestani, Arash. Submitted to: *Review of Managerial Sciences* journal.

My contributions

Paper 1: Lead author: led the work with idea generation, conceptualization, study design, systematic review, analyses, syntheses, preparation of the original manuscript, and revisions.

Paper 2: Coauthor: contributing to all parts of the manuscript and project. This includes idea development, study design, literature review, analyzing and connecting the concepts, model development, preparation of the original manuscript, and revisions.

Paper 3: a solo paper

Paper 4: Lead author: led the work with idea development, study design, literature review, data collection, analyses, and preparation of the original manuscript.

1. Introduction

This section introduces the core elements of the thesis, foreshadowing the elaborations presented in subsequent sections. It begins by outlining the background, followed by elucidating the applied perspective and the research problem, laying the groundwork for proposing the research questions and purpose that guide this study. The section then delves into the thesis' empirical context and concludes by demarcating the scope and outlining the overall disposition.

1.1 Background

In 2008, Jonsson stated that customers not only want well-functioning and good-looking products but also want them at the precise time and place demanded, at a reasonable price. To achieve this, many processes are usually involved, such as material or component supply, transportation, warehousing, and production, together with a great deal of information flow (Jonsson, 2008). This implies the demanding nature of customers, which has logically escalated over time with the growth of market competition (Kamalirezaei et al., 2020; Azeem and Kotey, 2023). To meet the customers' expectations, businesses need to deal with make or buy decisions – procuring products and services through hierarchical structures or market-based mechanisms (Williamson, 1975; Ketchen and Giunipero, 2004). Firms usually do not work alone to meet customers' demands (Oghazi, 2009), making the "buy" decision inevitable. This gives rise to the development of supply chains – a network of actors developing raw materials into distributed products, extending from raw material suppliers to end-users (Handfield and Nichols, 2002; Ketchen and Giunipero, 2004). This network also encompasses post-sale phases, such as return and reverse logistics (Rogers et al., 2002; Jonsson, 2008). Various actors, such as manufacturers, retailers, and distributors, are within different supply chain networks (Akkermans et al., 2003). Some processes within this network are contained within a single actor's territory. In contrast, others traverse beyond one actor's territory, potentially spanning across the globe, depending on the supply chain context (Ketchen and Hult, 2007).

In today's world, we live in a digital era driven by digitalization, where various digital technologies have reshaped many aspects of life (Brennen and Kreiss, 2016). Digital technologies (hereafter "technologies") are defined as *all electrical devices which make use of information represented in digital form – such as binary code – to perform useful functions* (Hajkowicz and Dawson, 2018, p.4).

With the evolving landscape of technologies, features of the digital era are also changing. Now, technologies can store, process, and spread information more than ever and they bring distant locations closer (Muduli, 2014; Kushwaha, 2021). Modern

and advanced technologies are used ubiquitously. For example, artificial intelligence helps to diagnose diseases, save, and extend lives in the health sector; blockchain is used in public services for higher accessibility and accountability; big data analytics guide more accurate policymaking (United Nations, n.d.).

The implication of the modern digital era extends to the business world. This implication manifested in the Fourth Industrial Revolution (Industry 4.0), a term coined for the first time at the Hannover Fair in 2011 (Ghobakhloo, 2018; Karabegovic, Karabegovic, et al., 2020). In this regard, Tjahjono et al. (2017, p. 1176) say that Industry 4.0 is *defined by many as a global transformation of the manufacturing industry by the introduction of digitalization and the Internet, these transformations consider revolutionary improvements in the design and manufacturing processes.*

Industry 4.0 follows three industrial revolutions that occurred in the past (Karabegovic, Karabegovic et al., 2020). The first industrial revolution (i.e., Industry 1.0), beginning in the 18th century, denotes mechanization and steam power, both of which boosted production; the second industrial revolution (Industry 2.0), starting in the 19th century, began with the advent of electricity and its subsequent effects, Engendering the modern world; the third industrial revolution (Industry 3.0), in the 20th century, occurred with the arrival of the internet, computers, and early technologies through which most industries have experienced significant changes and reformations (Schwab and Davis, 2018; Karabegovic, Karabegovic, et al., 2020; Christopher, 2021).

Industry 4.0 enables smart factories – that is, a *system of intelligent and networked machines with smart sensors* (Rashid and Tjahjono, 2016, p. 837). Such a network establishment occurs with various specific goals often pre-formulated (Tang et al., 2016; Shao et al., 2021). Industry 4.0 presents the business environment, enabling people and machines to become interconnected and integrated through advanced technologies (Oberg and Graham, 2016, as cited in Fatorachian and Kazemi, 2021). Wang et al. (2016) discuss that in a manufacturing environment under Industry 4.0, four layers of activities occur (as cited in Shao et al., 2021). The first layer involves machines (and their inter-communications), the shop floor, and all the tangible activities; the second layer refers to the transmission of data captured from the physical layer (through utilizing technologies like embedded sensors) to the cloud; the third layer is about generating intelligence via analyses on captured data (through analytical tools and software); and the fourth layer revolves around human supervision and control. From the use of Industry 4.0 in factories, automation associated with fewer human interventions occurs (Wuest et al., 2016); data-driven simulations and strategies are shaping up, together with all-round activities' optimization and monitoring (Tao et al., 2018); and improved process efficiency as well as enhanced product performance arise (Shao et al., 2021).

Furthermore, the literature has highlighted that the scope of Industry 4.0 technologies can extend beyond the confines of manufacturing, permeating throughout the supply chain, encompassing upstream and downstream processes (Tjahjono et al.,

2017; Fatorachian and Kazemi, 2021). This focal point has given rise to the concept of Supply Chain 4.0, denoting the application of advanced technologies within the supply chain context (Frederico et al., 2019; Asadollahi-Yazdi et al., 2020).

Technologies are enablers of Supply Chain 4.0 (Frederico, 2018; Makris et al., 2019; Frederico et al., 2019; Fatorachian and Kazemi, 2021). This implies that Supply Chain 4.0 engenders a technological transition within conventional supply chains. In this regard, Geels (2002, p. 1257) defines technological transition as *major technological transformations in the way societal functions such as transportation, communication, housing, feeding, are fulfilled. […] An example is the transition in offices from punched card technology and small office technology to digital computers, 1930–1960 (Van den Ende and Kemp, 1999).* In this thesis, Supply Chain 4.0 embodies this technological transition, representing a shift in conventional supply chains underpinned by the technologies of Supply Chain 4.0. Thus, within the context of this thesis, the transition to Supply Chain 4.0 is defined as a technological transformation in the way supply chains work, characterized by the adoption of advanced technologies such as the Internet of Things and artificial intelligence. In addition to technological acquisition, this transition includes reorganizing conventional supply chains (Barata, 2021; Frederico, 2021; Ali and Aboelmaged, 2022; Mahmoudi et al., 2022). To fully harness the potential unleashed by the transition to Supply Chain 4.0, conventional supply chains must undergo a comprehensive realignment of their existing ways of working and capabilities.

1.2 Applied perspective and problem discussion

Supply Chain 4.0 is gaining widespread recognition. A 2016 report by PricewaterhouseCoopers (PwC) revealed that one-third of more than 2000 respondents stated that their companies had already initiated the transition to Supply Chain 4.0 (Schrauf and Berttram, 2016), underscoring the growing popularity of this trend. The literature also highlights the potential significance of Industry 4.0 in the supply chain context, both during and after the COVID-19 pandemic (Frederico et al., 2023; Spieske et al., 2023). Large firms such as Rolls-Royce, Rio Tinto, AB InBev, Walmart, Gazprom, Volkswagen, and Bosch have been collaborating with their supply chain partners to harness disruptive technologies that underpin Supply Chain 4.0 (Frederico, 2018; Khatri, 2019). For example, Volkswagen, a German automotive manufacturer, utilizes HP's "Metal Jet" technology for advanced 3D printing of parts (Frederico, 2018). Bosch leverages the Internet of Things and cloud technologies to enhance vehicle capabilities (Rajagopal et al., 2018), while Danish company Maersk utilizes IoT and blockchain to improve transparency, efficiency, and safety in sea freight operations, as well as to replace hardcopies (Li, 2018). Furthermore, Industry 4.0 technologies have paved the way for startups to focus on innovative developments in the supply chain. For instance, ShipChain utilizes blockchain to enable smart

contracts within logistics operations (Choi et al., 2019), and Kiwi employs artificial intelligence to provide seamless solutions for food delivery (Younis et al., 2022).

However, despite the growing trend, a report by the World Economic Forum indicates that 70% of companies that ventured into Industry 4.0 technologies struggled to make significant progress in adopting and using them (Chmiko and Hutchison, 2023). This complexity is further amplified in the context of Supply Chain 4.0, which involves upstream and/or downstream actors extending beyond individual firms, operating within the intricate interplay of physical and digital spaces in the digital era amidst the intense and multi-directional information environment (Ferrantino and Koten, 2019; Preindl et al., 2020; Antai and Mutshinda, 2021; Veile et al., 2022).

Struggles for a successful transition to Supply Chain 4.0 can be exacerbated in developing economies due to their often more limited access to suitable infrastructure, workforce, and mechanisms, leading to heightened reliance on the technology sectors of developed economies to facilitate their technological transitions because of the stronger advancement and growth of technology industries therein (Ein-Dor et al., 1997; Dzyubenko, 2021; Marinas et al., 2021; Monasterio Astobiza et al., 2022).

The reliance of technology adopters on technology industries, along with the underlying natural evolution of the broader technological landscape, highlights the multi-level characteristic of technological transition. In this regard, Geels' (2002) multi-level perspective (MLP) emphasizes these multiple levels and their linkages. The MLP outlines three connected levels for technological transition: Regimes, Niches, and Landscape (for more details on MLP, please refer to section 1.4). Consistent with the aforementioned statements, technology-adopting firms in both developed and developing economies are Regime actors that rely on technology industries (i.e., Niche actors), often in developed economies, for transition to Supply Chain 4.0. Niche actors develop and provide technological solutions[1] utilizing advancements in the broader technological landscape.

Furthermore, variations in how Regime firms acquire technologies in the broader technological landscape from Niche actors, and how subsequently they align with them, engender differences in the success of firms during such technological transitions. Marinas et al. (2021) highlight such disparities among firms, which can be attributed to their abilities to harness these technologies effectively and can be linked to what is referred to as "dynamic capabilities". According to Teece et al. (1997), dynamic capability refers to *the firm's ability to integrate, build, and reconfigure internal and external competences to address rapidly changing environments* (p. 516). Teece's dynamic capabilities theory (2019) provides a framework elucidating how firms can comprehend technological advancements across an ever-evolving technological landscape, assimilate them, and align with them to maximize their utility. Dynamic capability emerges as a counterpoint to the static nature of the resource-based view (RBV), which largely overlooks the significance of assimilating resources

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[1] In this thesis, "technological solution" signifies tailoring technologies to address a specific context.

beyond the firm's confines (Teece, 2007, 2019). Dynamic capabilities enable firms to ensure that they effectively utilize the emerging opportunities in the broader landscape. While prior research has explored the impact of Supply Chain 4.0 on enhancing dynamic capabilities (Eslami et al., 2021; de Oliveira-Dias et al., 2023), the role of dynamic capabilities itself in facilitating the transition to Supply Chain 4.0 can also be an important consideration, yet underexplored. Additionally, the theoretical concept of "business-IT alignment" (hereafter referred to as business-technology alignment) implies that the process of alignment includes pertinent efforts not only from the adopting actor but also the technology solution provider (Luftman, 2004; Duffy, 2002, as cited in De Haes and Van Grembergen, 2009). This is consistent with Antony et al.'s (2023) emphasis on matching such a technological solution with the strategy of the adopting organization.

From the literature perspective, the domain of Supply Chain 4.0 remains underdeveloped, insufficiently researched in academia, and limited in conceptualization (Büyüközkan and Göçer, 2018; Frederico et al., 2019). This can be attributed, in part, to the novelty of the concept. The term "Industry 4.0" was only coined in 2011, and according to McKinsey & Company, Google searches for "Industry 4.0" were "practically nonexistent" before 2014 ("What are Industry 4.0," 2022). Supply Chain 4.0 emerged as an academic discourse even later. Luthra and Mangla (2018, p. 168 & 169) assert that *the majority of studies on Industry 4.0 considered the manufacturing sector context and ignored the supply chain system*.

Additionally, by examining the historical timeline and the gradual maturation of previous revolutions, notably Industry 3.0, one can argue that Industry 4.0 and its subsequent Supply Chain 4.0 are still nascent, with a long journey ahead. The advent of early digital technologies and the internet in the 1950s and 1960s laid the foundation for the third industrial revolution (Schwab and Davis, 2018; Karabegovic, Karabegovic et al., 2020). However, the World Wide Web (WWW) took over two decades to become fully operational. It is worth noting that certain forms of digital information transmission, a central feature of the third revolution (Schwab and Davis, 2018), required greater infrastructure and technological advancements beyond the status of WWW in the early 1990s.

From the underdeveloped domain of Supply Chain 4.0 in both practice and academia, there are signs in some of the literature that suggest a transition to Supply Chain 5.0 (Frederico, 2021; Villar et al., 2023). Supply chain 5.0 emphasizes achieving a balanced human-technological environment, with a focus on worker safety, social responsibility, sustainability, regulatory compliance, and ethical considerations, driven by Supply Chain 4.0 technologies, such as the Internet of Things and artificial intelligence, as well as newer technologies like 4D and 5D printing (Frederico, 2021). However, this thesis does not adhere to these emerging signs toward Supply Chain 5.0 for several reasons.

Firstly, there is no one-size-fits-all technological solution within the ambit of Supply Chain 4.0. Solutions range from complete automation to supporting human-

centric operations (see, for example, Paper 4), and they are context-dependent, taking into account factors such as market dynamics, strategic visions for Supply Chain 4.0, socio-cultural influences, cost-benefit analyses, and more.

A multitude of studies have described Supply Chain 4.0 as mainly involving the nearly end-to-end automation and integration of supply chain processes, such as production, transportation, and warehousing (e.g., Alicke et al., 2017; Fatorachian and Kazemi, 2021). In accordance with Fatorachian and Kazemi's (2021) conceptual description of Supply Chain 4.0, a set of sensors, tags, beacons, and actuators are embedded into numerous objects such as machinery, products, and devices, enabling machine-to-machine (M2M) communications and data sharing, thereby giving rise to a cyber-physical system (CPS) characterized by components' autonomy and connectivity. Different CPSs, from across the tiers of the supply chain, interconnect by linking to a central data server, which in turn connects to the internet, culminating in the formation of the Internet of Things (IoT). Within this IoT environment, advanced big data analytics technologies are employed to analyze the vast pool of data emanating from disparate CPSs. This fosters end-to-end automation and integration, as well as extensive data-driven insights.

While such a high level of automation and integration may be beneficial for some, it can significantly diminish the human role in supply chains, underscoring the need for conceptual advancements toward a more balanced approach (Cimini et al., 2020; Doyle Kent and Kopacek, 2021) – thus prompting the emergence of Supply Chain 5.0. There is no compelling requirement to associate Supply Chain 4.0 with complete automation and integration exclusively. Therefore, this thesis challenges the rigid emphasis on end-to-end automation and integration within Supply Chain 4.0, questioning the need to shift to Supply Chain 5.0 to achieve a balanced human-technological environment. The advanced technologies underlying Supply Chain 4.0 do not necessarily have to be implemented to achieve complete automation; diverse benefits can be derived from their adoption.

Secondly, safety, sustainability, social responsibility, and regulatory compliance considerations are not novel; they have been integral to business practices well before the advent of Supply Chain 4.0. Therefore, these considerations must naturally be factored into any implementation project. In addition, literature has shown the potential contribution of Supply Chain 4.0 to the aforementioned elements, such as environmental and social sustainability (Daú et al., 2019; Naseem and Yang, 2021).

Thirdly, while technologies like 4D printing are under development, they are essentially part of the same technological family as 3D printing, and their full potential and integration into supply chains are still evolving. Furthermore, although the technologies underpinning Supply Chain 4.0 are subject to ongoing discussions and refinement, it would be premature to definitively conclude that these technologies are set in stone and immune to significant replacement or enhancement.

Scholarly efforts in three sub-domains – namely, the benefits, challenges, and critical factors associated with this phenomenon – can be important to advance the

domain of Supply Chain 4.0. This study justifies the importance of investigating these three sub-domains with the following arguments.

1.2.1 Benefits of transition to Supply Chain 4.0

An important aspect in advancing the maturity of this domain is the investigation of the benefits of transitioning to Supply Chain 4.0. Govindan et al. (2022) emphasize that firms demand more knowledge regarding the benefits of embracing Supply Chain 4.0. Naseem and Yang (2021) highlight a gap in understanding, particularly among small and medium-sized enterprises, with respect to these pertinent benefits. Obtaining clear insights into these benefits is crucial for a relevant transition to Supply Chain 4.0 and empowers decision-makers to develop a realistic vision of the role that this concept can play in shaping their future (Büyüközkan and Göçer, 2018; Frederico et al., 2019).

Furthermore, as Supply Chain 4.0 is inherently technology-driven, comprehending the implications that the underlying technologies bring to the table plays a pivotal role in the decisions made by managers regarding the selection and adoption of these technologies within their supply chains. This perspective aligns with the "relative advantage" determinant, one of five attributes of innovation identified by Rogers (2003). Among these attributes, "relative advantage" holds particular significance in the adoption decision-making regarding technologies (Premkumar et al., 1994; Sun et al., 2020). Specifically, "relative advantage" addresses the perceived benefits that firms associate with evaluating new technologies; if the evaluation demonstrates that the technology is beneficial for the business, it serves as a motivating factor for adoption, and vice versa (Premkumar and Roberts, 1999; Sun et al., 2020).

Van Hoek et al. (2019) highlight that supply chain managers, without a clear understanding of the potential benefits and challenges posed by technologies, often hesitate to adopt them, even when acknowledging their potential. Focusing on blockchain, one of the technologies commonly associated with Supply Chain 4.0, Van Hoek et al. (2019, p. 2) say that *when we talk to supply chain practitioners about blockchain, it's not surprising that they typically respond with something like this: "I don't really understand it. I don't really know what to do with it, I don't know exactly how it applies to our business. I just know that I need to figure it out. But I have no clue how to begin."* A lack of sufficient knowledge regarding the implications of Supply Chain 4.0 and its underlying technologies, including blockchain, can give rise to business problems related to relevant adoptions and utilization.

Despite the evident significance of gaining a clear understanding of the benefits associated with transitioning to Supply Chain 4.0, the existing literature reveals a dearth of pertinent research and a lack of a comprehensive view of this aspect (Tjahjono et al., 2017; Büyüközkan and Göçer, 2018; Frederico et al., 2019; Hahn, 2020). Consequently, a comprehensive understanding of the benefits of transitioning to Supply Chain 4.0 is relevant for practice and research.

1.2.2 Challenges in transition to Supply Chain 4.0

Supply Chain 4.0 is still in its infancy (Tjahjono et al., 2017; Büyüközkan and Göçer, 2018; Frederico et al., 2019). This characteristic, combined with the continuous evolution of the underlying technologies in question (Schwab and Davis, 2018; Manners-Bell and Lyon, 2019), suggests potential challenges that could hinder the transition to Supply Chain 4.0.

While the potential benefits are central targets, transition to Supply Chain 4.0 potentially faces specific challenges along its path to success (Manners-Bell and Lyon, 2019; Antony et al., 2023). Given the limited number of successful transition cases observed in practice (Chmiko and Hutchison, 2023), it would be naive to expect a smooth transition without encountering hindering elements along the way.

The presence of challenges in adopting technologies in pursuit of Supply Chain 4.0 can also impact pertinent investment decisions, as they have the potential to hinder the transition process (Van Hoek et al., 2019; Ali and Aboelmaged, 2022). In this regard, Abdirad and Krishnan (2021) note that there are challenges in transitioning to Supply Chain 4.0, and for many managers, it is unknown whether the weight of benefits is sufficiently compelling for undertaking such implementations accompanied with a dearth of relevant experts in this area.

Given that this subject is relatively under-researched in the literature domain (Büyüközkan and Göçer, 2018; de Campos Martins and Simon, 2018; Ali and Aboelmaged, 2022), it becomes vital to understand the challenges that could hinder the transition to Supply Chain 4.0. For clarification, some examples of such challenges include high costs and security issues (Bär et al., 2018; Eslami et al., 2021).

1.2.3 Critical Factors in transition to Supply Chain 4.0

In addition to the challenges that can hinder the transition to Supply Chain 4.0, "critical factors" must be addressed to facilitate such a transition. Critical factors refer to those elements that, if properly dealt with, can substantially improve the chances of achieving the desired enhancements driven by the system (Pinto and Rouhiainen, 2001, as cited in Nasir and Sahibuddin, 2011).

Manners-Bell and Lyon (2019) argue that the attractiveness of technologies for adoption depends on the preparedness of the hosting ecosystem. Similarly, Remane et al. (2017) emphasize that, in addition to recognizing the digital impact, businesses must have the necessary "readiness" for the technological transition.

In line with these statements, it is important to pay great attention to the essential elements needed to prepare for a successful transition to Supply Chain 4.0 (Frederico et al., 2019). These essential elements can be called critical factors (Black and Porter, 1996; Sun et al., 2008; de Jesus et al., 2016). This thesis has already argued that in addition to acquiring technologies, conventional supply chains need to be aligned to harness the potential of this transition. Critical factors are essential elements to consider during such alignment.

Nevertheless, Büyüközkan and Göçer (2018) argue that despite the various benefits, the number of supply chains that have successfully established mature digitalization is limited due to a lack of clear insight into critical factors. For clarification, some critical factors include managerial support and commitment to Supply Chain 4.0 or knowledge development for this purpose (Frazzon et al., 2019; Frederico et al., 2019).

Moreover, in its current state, the literature within the domain of Supply Chain 4.0 presents diverse perspectives regarding the composition of underlying technologies, at times associated with unclear boundaries for the technologies considered (e.g., Tjahjono et al., 2017; Büyüközkan and Göçer, 2018; Makris et al., 2019). This lack of clarity can impede a comprehensive understanding of the benefits, challenges, and critical factors related to the pertinent transition. Besides, some scholarly endeavors in this area (e.g., Frederico et al., 2019) tend to over-summarize their analyses at the level of underlying technologies despite acknowledging their significance, potentially missing opportunities for more targeted contributions.

1.3 Research purpose, questions, and empirical context

The overarching purpose of this thesis is to advance the frontiers of knowledge in the domain of Supply Chain 4.0. This broad purpose is delineated into two specific ones:

A. To understand the benefits and challenges of the transition to Supply Chain 4.0.
B. To illuminate the critical factors necessary to successfully transition to Supply Chain 4.0.

In light of these purposes, three research questions have been formulated for examination through the investigations that were conducted. These three research questions (RQs) are as follows:

RQ 1: What are the benefits of transitioning to Supply Chain 4.0?
RQ 2:What are the challenges related to the transition to Supply Chain 4.0?
RQ 3: What critical factors are necessary for transitioning to Supply Chain 4.0?

"Benefits" refer to the contributing elements in supply chains that can be achieved through a successful transition to Supply Chain 4.0. "Challenges" pertain to the hindering elements that supply chains may encounter in transitioning to Supply Chain 4.0. "Critical factors" are those elements that, if properly dealt with, can substantially improve the chances of a successful transition to Supply Chain 4.0.

In light of these research questions, this thesis employs a multimethod approach, encompassing four studies (details can be found in the Methodology section – Section 3).

An overview of the research purposes and questions is presented in Table 1.

Table 1: Research purposes and questions

Overarching research purpose To advance the knowledge frontiers in the domain of Supply Chain 4.0.	
Research purpose A To understand the benefits and challenges of the transition to supply chain 4.0.	**Research purpose B** To illuminate the critical factors necessary to successfully transition to Supply Chain 4.0.
Research question 1 What are the benefits of transitioning to Supply Chain 4.0? **Research Question 2** What are the challenges related to the transition to Supply Chain 4.0?	**Research question 3** What critical factors are necessary for transitioning to Supply Chain 4.0?

The empirical focus of this thesis centers on a case study involving a technological transition within a firm situated in a developing economy – Turkey (Karadag, 2017; Ersoz et al., 2022). This transition is facilitated by a technological solution developed by a firm in a developed economy – Sweden. As previously noted, adopting and utilizing Supply Chain 4.0 technologies often present complications. These complications are further pronounced for firms in developing economies, which frequently rely on the technology industries of developed economies. Therefore, this case study offers valuable insights into similar contexts, shedding light on various facets associated with technological transitions in developing economies.

Furthermore, Turkey, recognized as a global hub for logistics due to its strategic geographic location (Özdemir, 2010; Acar et al., 2015; Acar et al., 2020), is actively striving to bolster its competitive edge in the dynamic business world by embracing the transformative power of advanced technologies. According to the Minister of Science, Industry and Technology of Turkey in 2018, Faruk Ozlu, *countries which equip their schools, factories, cities and armies with technology become powerful and continue to be strong* (as cited in Gungor, 2018).

This stance is evidenced by encouraging initiatives spearheaded by the Turkish government aimed at fostering digitalization across various sectors (Duman and

Akdemir, 2021) and by Turkey's rising demand for reducing the costs of business conduct facilitated by these technologies (Ersoz et al., 2018; Cergibozan and Tasan, 2022). One of these initiatives is Turkey's Digital Transformation Roadmap, which is targeted at nurturing digitalization and enhancing the country's digital infrastructure and capabilities. In this regard, the Development Minister of Turkey in 2017 says that *we will improve infrastructure for domestic production and the efficient use of high technologies such as the internet of things, robotics, big data, artificial intelligence and augmented reality* (as cited in Sahin and Zengin, 2017).

However, Turkey has made limited progress in its transition to advanced technologies (Atik and Ünlü, 2019; Izmen et al., 2020). Hence, case insights from a transition in Turkey can pave the way for other businesses in Turkey to embark on such a journey.

1.4 Thesis demarcation

As noted earlier, the transition to Supply Chain 4.0 includes actors and contexts on multiple levels: the technological solution provider; the adopting supply chain actor(s), and the advancement in the broader technological landscape that enables the development of Supply Chain 4.0 solutions. In this regard, Geel's (2002) MLP, including Regimes, Niches, and Landscape, accounts for such a multi-tiered feature of the transition to Supply Chain 4.0.

The *Regime* level encompasses actors with set establishments, rules, and configurations (e.g., capabilities, competencies, practices) characterized by lock-in and stable trajectories (Geels, 2002 & 2011). Technological innovations occurring within the actors at the Regime level often have an incremental nature, not radical (Geels, 2002), potentially because of sunk costs and grounded business complementarities, favoring relatively more stable trajectories (Stalmokaitė, 2021). The *Niche* level, including actors such as entrepreneurs, start-ups, and spinoffs, function as incubation rooms, working on radical innovations that often emerge outside or on the fringe of existing regimes (Grin et al., 2010; Geels, 2011). Niche actors often drive radical innovations (Stalmokaitė, 2021). The *landscape* is the context involving a broad arrangement of components such as political landscape (e.g., political coalitions), economic landscape (e.g., oil prices or economic growth), and socio-demographic landscape (e.g., emigration or cultural values), often beyond the scope of influence of actors in Regime and Niche levels (Geels, 2002 & 2011).

Embracing Geels' (2002) MLP, Supply Chain 4.0 preceded by broader digitalization, shaping a technological landscape where advanced technologies emerged with the potential for engendering disruptive impact into many aspects of life, broader than business, such as self-driving cars (Preindl et al., 2020). The niche level includes actors that are radical innovators who harness the potential of this technological landscape for the business world. These actors are advanced technological solution providers for the manufacturing sector (Industry 4.0) or wider upstream and down-

stream tiers (Supply Chain 4.0). In the present thesis, regime actors are status quo supply chains (including manufacturers, distributors, retailers, suppliers, Enterprise Resource Planning (ERP) developers, etc.) with stable and established business trajectories. While the broader landscape is inevitable in this equation (such as governmental regulations, technological advancements, and economic conditions), the central scope of this research falls into the Niche-Regime interaction for transitioning to Supply Chain 4.0.

While MLP serves as the basis for demarcation of this thesis, dynamic capabilities theory emerges as a fitting account for the process of transitioning to Supply Chain 4.0. To this end, delving into the trio of benefits, challenges, and critical factors associated with Supply Chain 4.0, valuable insights can be gleaned for the adaptation of supply chain actors' dynamic capabilities, by enabling them to better comprehend the upsides and downsides posed by transition to Supply Chain 4.0 and to understand the critical factors necessary for successful alignment. More so, applying the theoretical concept of business-technology alignment, this thesis builds on dynamic capabilities theory by asserting that successful alignment is a two-sided effort between the Niche technological solution provider and the Regime's adopting actor(s) (for more details on the interplay between the trio and the thesis theoretical framework, please refer to sections 2.3 and 2.4).

1.5 Disposition

The following section delves into the relevant literature, focusing on the core elements introduced in the thesis' introduction. Section two further elaborates on the theoretical underpinnings, laying the foundation for the thesis framework that guides subsequent investigations. Section three outlines the chosen methodologies, employed studies, and the rationale behind their selection. Section four presents the results of the four papers developed from the four studies included in this thesis. Section five offers in-depth discussions based on the findings from the thesis studies, addressing the questions posed by the thesis. Finally, in section six, the concluding remarks, implications, limitations, and directions for future research are provided.

2. Frame of reference

This section elaborates on the core elements of this thesis through a survey of relevant literature. It begins by delving into the concept of Supply Chain 4.0, elucidating factors that limit its current conceptualization and developing a conceptual basis for further pertinent investigations. Next, it expounds supply chain management, emphasizing a strategic management perspective. Drawing upon the strategic management domain, the section then develops the theoretical considerations that guide this research. Ultimately, this section culminates in the synthesis of key intellectual elements, leading to the establishment of a framework for this thesis.

2.1 Supply Chain 4.0

While businesses exhibit diversity in their selection of technologies, it is evident that technology serves as the core underlier of Supply Chain 4.0 (Frederico, 2018; Makris et al., 2019; Frederico et al., 2019; Fatorachian and Kazemi, 2021). Configuration of underlying technologies in Supply Chain 4.0 varies across supply chains, depending on the needs of the hosts and possible technological complementarities. For instance, Rejeb et al. (2019) highlight the potential synergy between IoT and blockchain for data transfer, with enhanced data security and auditability. Similarly, Pournader et al. (2021) underscores the incorporation of Artificial Intelligence into simulation technology to facilitate advanced scenario-based analysis.

The technological nature of Supply Chain 4.0 is also reflected in maturity models. For instance, five distinct maturity levels are delineated in an Industry 4.0 maturity model designed for Operations and Supply Chain Management by Caiado et al. (2021). The lowest level signifies a business environment where advanced and disruptive digital technologies are nearly absent. In contrast, the highest maturity level signifies the presence of a robust technological infrastructure.

Furthermore, Benitez et al. (2021) imply that the technological complementarity inherent in Supply Chain 4.0 solutions emphasizes the need for a network-centric perspective on supply chains, instead of the traditional linear supply chain relationships, better suited to provide the requisite technological infrastructure.

Next, Shao et al. (2021), utilizing a qualitative case study approach, have developed a multistage framework for implementing Industry 4.0 within supply chains. This framework comprises four stages. The initial stage serves as the trigger for establishing the foundations of Supply Chain 4.0, primarily within the sphere of a champion actor. The second stage centers on the champion firm establishing connections with its suppliers. In the third stage, the emphasis shifts toward consolidating connectivity with suppliers through the exchange and matching of data. This stage also involves

the extension of connectivity to a third actor within the network. Additionally, the third stage encompasses multi-tier collaboration and data linkage with a centralized networked system. Ultimately, the fourth and final stage entails the combination of the information landscape and implementing corrective measures.

2.1.1 Factors contributing to the limited conceptualization of Supply Chain 4.0

Supply Chain 4.0 lacks a robust conceptualization, a recognized shortcoming in the literature (Tjahjono et al., 2017; Büyüközkan and Göçer, 2018; Frazzon et al., 2019; Frederico et al., 2019; Fatorachian and Kazemi, 2021). This gap, attributed partly to the emerging nature of the domain, can also be investigated from other perspectives. One significant aspect is linked to the composition of the technology collection or package that underlies the transition to Supply Chain 4.0. Despite this recognition, the literature has no consensus regarding these underlying technologies. Table 2 illustrates several attempts made to identify these underlying technologies.

As shown in Table 2, while there exist elements of commonality, a consensus on the specific technology set underlying the transition to Supply Chain 4.0 remains elusive. This can be attributed to the fact that supply chains transit to Supply Chain 4.0 to serve their individual objectives and contexts, making it challenging to define a universal technology package capable of addressing all needs. In such a naturally fluid environment, pinpointing universal and precise features, downsides, and upsides associated with Supply Chain 4.0 proves intricate, as each technology in play offers distinct characteristics. For instance, the benefits and challenges of blockchain differ from those of 3D printing or robotics.

The dearth of in-depth technological analyses is another inhibiting factor in achieving a robust conceptualization of Supply Chain 4.0. Endeavors to develop corresponding conceptualizations require pertinent analyses for each technology in question (e.g., Tjahjono et al., 2017; Büyüközkan and Göçer, 2018).

Table 2: Categorization of technologies underlying Supply Chain 4.0

Study	Categorization of underlying technologies for Supply Chain 4.0
(Tjahjono et al., 2017)	Virtual and augmented reality, 3D printing, simulation, big data analytics, cloud technology, cyber security, Internet of Things, miniaturization of electronics, automation identification and data collection, radio frequency identification, robotics, drones and nanotechnology, machine to machine communication, business intelligence
(Frederico, 2018)	Internet of Things, cyber physical systems, big data analytics, 3D printing, robotics and artificial intelligence, radio frequency identification, cyber security systems (blockchain), cloud technology
(Büyüközkan and Göçer, 2018)	Augmented reality, big data, cloud computing, Internet of Things, nanotechnology, omni channel technologies, robotics, sensor technology, self-driving vehicles, unmanned aerial vehicles, 3D printing
(Junge, 2019)	Information and communication technologies, auto identification technologies, cloud technologies, analytics technologies, blockchain, cyber physical systems, automation technologies, virtual and augmented reality, additive manufacturing
(Makris et al., 2019)	Big data technologies, cloud computing, 3D printing, cyber physical systems, Internet of Things, Internet of Services, smart technologies, machine learning
(Fatorachian and Kazemi, 2021)	Cyber physical systems, Internet of Things, big data analytics, cloud technologies

However, not all studies incorporate such a comprehensive technological perspective. For instance, based on a systematic literature review, Frederico et al. (2019) aimed to conceptualize Supply Chain 4.0 by dividing it into four connected categories. The first category, "managerial and capability supporters", identifies dimensions that reflect capabilities and management issues supporting Supply Chain 4.0. The second category, "technology levers", highlights 21 technologies underpinning Supply Chain 4.0. The third category, "process performance requirements", underscores the enablers of Supply Chain 4.0. Finally, the last category elaborates on the "strategic outcomes". While this study is valuable to Supply Chain 4.0 research, it falls short in providing comprehensive considerations at the technology level. Despite recognizing the underlying role of technologies in Supply Chain 4.0, Frederico et al. (2019) discuss the aspects in question largely irrespective of the characteristics of the underlying technologies themselves. Although there are brief examples, *disruptive technologies such as 3DP, AI, SM, and Rb are key to achieving more responsiveness and flexibility*

(p. 275)[2]. Nevertheless, deeper technological investigations are required to better conceptualize the subject.

Hence, it can be asserted that Supply Chain 4.0's emerging nature, its naturally fluid environment, and the limited depth of technological analyses have collectively impeded the development of a robust conceptualization.

2.1.2 Supply Chain 4.0: developing a conceptual basis for further investigations

This thesis, positioned as an endeavor to further the understanding of the Supply Chain 4.0 domain, seeks to delineate the benefits, challenges, and critical factors associated with transition to Supply Chain 4.0. To fulfill this objective, the aforementioned three elements (i.e., the emerging nature of Supply Chain 4.0, its naturally fluid environment, and the limited depth of technological analyses) must be addressed in line with the purposes of this thesis (see introductory section for the purposes). To achieve this, the thesis has taken a dual-pronged approach, conducting a focused examination of both the general level of Supply Chain 4.0 and the specific technologies that underlie it. This approach addresses all three elements: firstly, it contributes to the advancement of the subject domain by delving into the benefits, challenges, and critical factors associated with Supply Chain 4.0 and its technologies; secondly, by identifying and explicitly concentrating on the underlying technologies of Supply Chain 4.0, it reasonably responds to its inherent naturally fluid environment; thirdly, it broadens the analytical perspective to the technology level, an aspect that has been limitedly elaborated in previous research efforts.

Hence, drawing upon the body of literature within the supply chain research domain (Tjahjono et al., 2017; Frederico, 2018; Büyüközkan and Göçer, 2018; Junge, 2019; Makris et al., 2019; Fatorachian and Kazemi, 2021), and beyond (Ghobakhloo, 2018; Schwab and Davis, 2018; Karabegovic, Karabegovic, et al., 2020), a set of advanced technologies commonly associated with Supply Chain 4.0 (hereafter referred to as "Supply Chain 4.0 technologies") has been identified. These technologies encompass the Internet of People (IoP), Internet of Things (IoT), cloud computing (CC), big data technologies (BDTs), blockchain (BC), augmented reality (AR), automation (AU), robotics (RO), additive manufacturing (AM), simulation (SI), semantic technologies (ST), and artificial intelligence (AI). A brief description of each of these twelve technologies is presented in Table 3.

These twelve Supply Chain 4.0 technologies demonstrate significant applicability within the realm of supply chains. Several technologies considered in previous studies have been consolidated into a single category due to their similarity. For instance, unmanned vehicles (Büyüközkan and Göçer, 2018), and drones (Tjahjono et al., 2017), have been grouped under RO, aligning with related literature (Cavoukian, 2012; Hassanalian and Abdelkefi, 2017). Similarly, radio frequency identification

[2] 3DP (three-dimensional printing), AI (artificial intelligence), SM (smart machines), Rb (robotics)

(RFID) has been considered a subset of IoT (see Jia et al., 2012). One technology often associated with Supply Chain 4.0 is CPS. However, CPS has been excluded from this list due to its substantial overlap with IoT, as supported by studies (Bordel et al., 2017; Xu et al., 2018). Furthermore, it has already been explained how Fatorachian and Kazemi (2021) describe CPS as an integral part of IoT.

Next, out of the twelve Supply Chain 4.0 technologies, this thesis recognizes four as base technologies – i.e., the enabling technologies of Supply Chain 4.0. These four base technologies include the Internet of Things, artificial intelligence, cloud computing, and blockchain. Although these four technologies have been acknowledged as vital in the literature (e.g., Frederico, 2018; Büyüközkan and Göçer, 2018; Junge, 2019; Makris et al., 2019; Fatorachian and Kazemi, 2021), this thesis does not solely rely on previous literature. Instead, it justifies the selection of these four technologies using three arguments: technological pervasiveness; technological dynamism; and their central role in configuring Supply Chain 4.0.

Table 3: Descriptions of Supply Chain 4.0 technologies

Supply Chain 4.0 technologies	Descriptions	Inspiring sources for descriptions
Internet of Things (IoT)	Technology that interconnects physical objects (e.g., consumer products, equipment, machineries) with one another and with the outside world, via which objects-related data can be gathered, processed, and communicated.	(Schwab and Davis, 2018; Frederico, 2018; Boyes et al., 2018)
Internet of People (IoP)	Technology through which users' information can be gathered from online platforms (e.g., Facebook) and be utilized for various business purposes such as targeted marketing and trend forecasting.	(Ghobakhloo, 2018)
Cloud computing (CC)	Technology that brings services, computation, storage, and applications on cloud/internet.	(Stergiou et al., 2018)
Big data technologies (BDT)	Technology that offers possibility to manipulate and analyze diversified and large amount of data for creating knowledge and information.	(Ghobakhloo, 2018; Frederico, 2018)
Blockchain (BC)	It is a distributed ledger technology that establishes a secure and largely visible database of digital contents (e.g., information and transactions) among participants.	(Schwab and Davis, 2018; Van Hoek et al., 2019)
Augmented reality (AR)	Technology via which computer graphics are superimposed on the real environment.	(Yew et al., 2016)
Automation (AU)	Utilizes CPS properties to enable the network of self-conducting activities and processes. In this thesis, automation is mainly based on predictable conditions and centers on repetitive tasks.	(Lu, 2017; Frederico, 2018)

Robotics (RO)	Centered on AI, it is a technology capable of cognition, navigation and mobility, and complex interaction.	(Schwab and Davis, 2018)
Artificial intelligence (AI)	It is capable of cognitive functions such as reasoning, meaning extraction, perception etc., which are normally undertaken by human intelligence.	(Hacibeyoglu et al., 2017; Hainc et al., 2017)
Additive manufacturing (AM)	Also known as 3D printing. Technology through which manufacturing characterizes by joining the materials layer upon layer, with the purpose of the creation of physical output from 3D model.	(Mellor et al., 2014; Schwab and Davis, 2018)
Simulation (SI)	Technology for imitation of systems to predict and evaluate their behavior and performance.	(Xu et al., 2016)
Semantic technologies (ST)	Technology for standardization of language and knowledge representation among various components and technologies.	(Ghobakhloo, 2018)

Technological pervasiveness

The concept of "technological pervasiveness" is underscored in the literature as a key factor for distinguishing technologies with widespread impact from those with limited influence (Bresnahan and Trajtenberg, 1995; Teece, 2018). In simple terms, pervasive technologies exist in most or all supply chain tiers. In this thesis, technological pervasiveness serves as one of the criteria for differentiating the base technologies of Supply Chain 4.0 from others. In accordance with this rationale, Fenn and Time (2007) categorize technologies into four groups based on their level of impact. According to their classification, "transformational" technologies are ranked highest due to their extensive scope of impact across various industry subsets (i.e., pervasiveness), contrasting with the three lower ranks encompassing technologies mainly manifested at the business process level.

Regarding the pervasiveness of the four base technologies, Manners-Bell and Lyon (2019) have defined supply chain processes as follows: 1. Product design/production/sourcing; 2. Warehousing; 3. Transport; 4. Last-mile delivery; 5. End of life/spare parts. They then position technologies within these processes in terms of usability and impact. In their categorization, BC, AI, IoT, and CC represent Supply Chain 4.0 technologies in all five of the aforementioned processes. AM is involved in the first and fifth processes, while RO primarily contributes to the second, third, and fourth processes. AU and AR are prominent in the second process. Additionally, by their nature, technologies like IoP and SI may not have a substantial presence in all tiers of the supply chain. ST and BDTs extend the IoT environment, where data streams are shaped, and AI is their key enabler.

The pervasiveness of IoT, AI, CC, and BC is unsurprising. Various IoT subsets can be observed throughout supply chain processes; for example, RFID is used in ware-

housing, GPS in transportation, and Industrial IoT (IIoT) in production. As distributed ledger systems, BC applications can span from raw material suppliers to production plants, distributors, and stores (see, for example, Van Hoek et al., 2019). CC underpins cloud storage and computation, serving as a conduit for interconnected data flows within Supply Chain 4.0. Even BC data is stored on the cloud (Van Hoek et al., 2019). AI is a dynamic technology which means that it proceeds into further technologies based on its principal function (see "technological dynamism" in Bresnahan and Trajtenberg, 1995).

Consequently, technologies leveraging AI as a core component are recurrent, including BDTs, RO, AU, etc. Thus, AI is a pervasive technology across various supply chain tiers. For instance, AI can be used in robots and AU in different supply chain layers, such as for production and advertising optimization (Dash et al., 2019).

Technological dynamism

In terms of technological dynamism, much like AI, IoT represents a significant element for driving other technologies, such as BDTs and RO. Within the conceptual description of Supply Chain 4.0 outlined by Fatorachian and Kazemi (2021), as previously discussed in this thesis, the importance of the IoT environment was underscored for aggregating data from various CPSs, thereby enabling the analysis of big data through BDTs. Similarly, IoT plays a crucial role in the realm of RO. One example involves the combination of IIoT with collaborative robots (Cobots) to facilitate the communication between Cobots and employees in the formation of an effective assembly system (Salunkhe et al., 2019).

CC represents another dynamic technology. For instance, CC supports BC applications (Van Hoek et al., 2019). Likewise, CC serves as a fundamental component within the IoT environment and the realm of BDTs (as elaborated in Fatorachian and Kazemi, 2021). Notably, CC is one of the four essential constituents of IoT architecture (Vyas et al., 2019, Figure 4.1).

BC can play a pivotal role in enhancing the security of the IoT environment, which can be susceptible to cyberattacks and threats (Hussain et al., 2021). Its ability for decentralization as a distributed ledger is particularly valuable in configurations where IoT devices are distributed across various organizations (such as within the context of the supply chain), and secure stream sharing is imperative (Vyas et al., 2019). Also, BC can facilitate the IoT/big data exchange between providers and consumers, who may be diverse actors within a supply chain consortium (Vyas et al., 2019). These statements clearly illustrate the technological dynamism of IoT, AI, CC, and BC, driving other technologies.

In short, this thesis posits that IoT, AI, CC, and BC are the base technologies of Supply Chain 4.0. This assertion is rooted in the pervasive presence of these four technologies across different supply chain tiers, further reinforced by their dynamic

nature. Additionally, a third argument supporting the classification of these four technologies as base ones lies in their central role within Supply Chain 4.0.

Central technologies of Supply Chain 4.0

As previously discussed, transition to Supply Chain 4.0 represents a technological transformation in the way that supply chains work. In this regard, three key disruptive characteristics can be associated with Supply Chain 4.0: object-to-object, object-to-human, human-to-object, and human-to-human *interconnectivity* (Wu et al., 2016; Jayaram 2016; Frederico, 2018; Frazzon et al., 2019; Sobb et al., 2020; Hahn, 2020; Aktas et al., 2021); *intelligence and transparency* on supply chain processes and activities (Wu et al., 2016; Frazzon et al., 2019; Hahn, 2020; Aktas et al., 2021), and *autonomy* capability with reduced human intervention (Wu et al., 2016; Jayaram 2016; Frazzon et al., 2019; Sobb et al., 2020; Hahn, 2020). In line with this representation of Supply Chain 4.0, the central roles of IoT, AI, CC, and BC can be linked to these key disruptive characteristics.

In Table 3, IoT is defined as a technology that connects physical objects to each other and the outside world, enabling data collection, processing, and communication from objects (Schwab and Davis, 2018; Frederico, 2018; Boyes et al., 2018). The embedding devices can generate data and provide computing capabilities for the objects for various purposes; for example, in the transportation of fresh foods, embedded sensors can measure the temperature of food boxes and stream the data content in real-time, which is useful for monitoring the condition of the transported goods (Vyas et al., 2019). Taking this example, it is evident that such an IoT-driven capability significantly enables two of the three key disruptive characteristics of Supply Chain 4.0: 1) interconnectivity, 2) intelligence and transparency.

Furthermore, IoT (Vyas et al., 2019) and even BC (Van Hoek et al., 2019), like some other technologies, use CC for their operations. Essentially, CC involves running server-side code on large-scale data center compute servers capable of remote client-data processing and management (Vyas et al., 2019). In a nutshell, CC involves the migration of data environments (e.g., storage, computation, application) to the cloud (Stergiou et al., 2018).

CC encompasses three service models: 1) Infrastructure as a Service (IaaS), where the application developer (the company that purchased the IaaS service) is responsible for designing and operating its software and data system; 2) Platform as a Service (PaaS), where the application developer uses pre-built software tools provided by the cloud service provider to simplify application design and operation; 3) Software as a Service (SaaS), where the cloud service provider hosts the entire software (Vyas et al., 2019).

Despite the chosen service model, BC and the IoT environment, along with other technologies like 3D printers, use CC. In the previously elaborated conceptual description of Supply Chain 4.0 (Fatorachian and Kazemi, 2021), it can be noticed

how CPSs equipped with sensors, RFID tags, actuators, and beacons connect to the cloud to create the IoT environment and enable big data analyses. Therefore, it is reasonable to argue for the central role of CC and IoT in the configuration of Supply Chain 4.0.

Next, Metaxiotis et al. (2003) categorized AI into three functionality-based groups: 1) expert systems; 2) Artificial neural networks; and 3) Intelligent agents (as cited in Meyer et al., 2020). The first type (i.e., expert systems) is a problem-solving tool, relying on its substantial knowledge base within the relevant domain. The second type involves systems trained to analyze available data for pattern recognition (this type underlies machine learning algorithms). The third type is capable of autonomous actions within a given environment, such as robots (Meyer et al., 2020). Across these three categories, it is evident that AI directly contributes to two of the three key disruptive characteristics of Supply Chain 4.0 discussed earlier: intelligence and autonomy. A systematic review conducted by Toorajipour et al. (2021) demonstrates that the most prevalent AI technique used in the supply chain context relates to information processing for discovering knowledge, models, and patterns. Similarly, Dubey et al. (2021) emphasize the significant role of AI in enhancing supply chain analytical capabilities, highlighting AI's potential to foster supply chain intelligence. As a key component of big data analytics, AI plays a crucial role in generating insights into various processes within the supply chain. AI is also a vital element of IoT and the connectivity it enables (Nahr et al., 2021).

BC offers a distributed database for data sharing and processing associated with immutability and authenticity (Vyas et al., 2019; Manners-Bell and Lyon, 2019; Van Hoek et al., 2019). The immutability feature of BC security guarantees that transferred data among actors cannot be modified and will remain unchanged. BC's authenticability mechanism holds the senders of data accountable by ensuring that no one else can produce that data. Hence, these BC qualities support the interconnectivity among supply chain actors. Another important application of BC is smart contracts (Toorajipour et al., 2022; Kordestani et al., 2023). By digitalizing the contractual arrangement, smart contracts enable the coordinated and automated implementation of transactions once the predetermined conditions are met (Chang et al., 2019; Saberi et al., 2019; Batwa and Norrman, 2020; Dolgui et al., 2020). This contributes to the autonomy of supply chains. In addition to interconnectivity and autonomy, "intelligence and transparency" account for the third disruptive characteristic of Supply Chain 4.0. BC enables transparency across the tiers of the supply chain (Manners-Bell and Lyon, 2019). In this regard, the possibility of keeping the transactions unlinkable to the source (but authenticable) and traceable using a tracking key enables actors to put information on the BC without fear of revealing their private data (Vyas et al., 2019). This feature, along with authenticability (i.e., no one can falsely replace an honest actor in the BC) and immutability (i.e., no one can change the content of the BC's data), can be significant for supply chain transparency.

The statements mentioned above shed light on the central role of the IoT, AI, CC, and BC in Supply Chain 4.0. Arguments regarding their central role, pervasiveness, and dynamism highlight these four as base technologies of Supply Chain 4.0.

2.2 Supply chain: a strategic management perspective

The roots of supply chain literature can be traced back to over half a century when Forrester's study in 1958 cast light on the importance of examining the interrelationships between separate companies (as cited in Mentzer et al., 2001). Although the popularization of supply chain concepts gained momentum in the 1980s (e.g., Oliver and Webber, 1982; Stevens, 1989).

The discourse surrounding supply chain and its relationship with supply chain management has been discussed in the relevant literature. Mentzer et al. (2001) assert the existence of a clear boundary between the supply chain and supply chain management. *The former is simply something that exists (often also referred to as distribution channels), while the latter requires overt management efforts by the organizations within the supply chain* (p. 4). Alternatively, other scholars propose a more intertwined boundary between supply chain and supply chain management. For instance, Lambert (2004) and Wisner et al. (2014) describe supply chain management as coordinating processes and activities within supply chains to create value for all actors. Christopher (2005) defines it as managing relationships among supply chain actors to achieve desired outcomes at the lowest cost. In this context, Christopher (2005, p. 5) characterizes the focus of supply chain management as the *management of relationships in order to achieve a more profitable outcome for all parties in the chain*. Ganeshan et al. (1999) emphasize that supply chains are managed as single entities through partnerships, requiring robust collaboration and coordination (as cited in Vyas et al., 2019).

Bechtel and Jayaram (1997) identify four schools of thought shaping supply chain management approaches. The "chain awareness school" recognizes functional areas for material flow within the supply chain. The "linkage school" highlights actual linkages between these functional areas. The "information school" acknowledges bidirectional information flow among supply chain members. The "integration school" emphasizes the business processes over static functional areas, viewing the supply chain as a system primarily focusing on customer satisfaction. In essence, supply chain integration denotes the ability of supply chain actors to conduct supply chain activities jointly (Forslund and Jonsson, 2007 & 2009).

Within the integration school, various theoretical frameworks for supply chain management have emerged, centering on business processes and integration. The Global Supply Chain Forum (GSCF) defines supply chain management as the integration of business processes, modeling supply chain management with three components: supply chain network structure; eight supply chain business processes; and management components (Lambert and Cooper 2000; Lambert et al., 2005;

Jonsson, 2008). The Supply-Chain Operations Reference model (SCOR), developed by the Supply Chain Council, further divides supply chain management into five processes: plan; source; make; deliver; and return (Stewart, 1997; Jonsson, 2008). Srivastava et al. (1999) emphasize integrating three key business processes: customer relationship management; product development management; and supply chain management. Additionally, Melnyk et al. (2000) offer a framework focusing on eight business processes, four of which align with SCOR's model.

A significant contribution to the supply chain domain stems from the research of Ketchen and Giunipero (2004), which bridges strategic management with supply chain management. According to their perspective, a supply chain embodies Leavitt's (1965) organizational constituents, including participants, social structure, goals, and technologies, such that it can be conceptualized as a "supra-organization" (Ketchen and Giunipero, 2004). Consequently, they introduce the "supply chain organization", describing it as *a relatively enduring interfirm cooperative that uses resources from participants to accomplish shared and independent goals of its members* (Ketchen and Giunipero, 2004, p. 55). This contribution is important, since it builds on business process integration toward developing and sustaining competitive advantages, thereby opening avenues for applying strategic management theories within the supply chain domain (Ketchen and Hult, 2007). As a field, strategic management predominantly concerns how organizations can create and maintain a competitive advantage (Ambrosini and Bowman, 2009). While supply chain integration remains important, strategic management encompasses a broader spectrum of perspectives, including resource dependency and strategic decision-making (Akyuz and Gursoy, 2020). The literature on the strategic management of supply chains underscores the potential for supply chains to serve as competitive weapons in the pursuit of sustained competitive advantage (Hult et al., 2007; Ketchen and Hult, 2007; Ketchen and Craighead, 2020). In this intellectual realm, within which the present thesis also resides, the supply chain can be viewed as a strategic organization (Chowdhury and Quaddus, 2017).

2.3 Theoretical consideration

Structure-Conduct-Performance (SCP) is an early fundamental paradigm in industrial organization that has played an essential role in the development of strategic management (Matyjas, 2014; Tell, 2020). SCP delineates the interplay between market structure (e.g., the number and size of firms and barriers to entry), firm conduct (activities of a strategic nature), and performance (financial performance), asserting that market structure shapes the conduct of firms, which in turn impacts a firm's performance (Bain, 1986; Matyjas, 2014). In SCP, the industry provides the main contingencies for profitability, implying, for example, that monopolists conduct themselves differently from firms under perfect competition, leading to differences in performances (Tell, 2020). Originally, the underlying assumption of the SCP

paradigm was that firms within an industry did not vary significantly in any strategically relevant aspect beyond the scale of their operations (Matyjas, 2014).

SCP was then met with criticism, emphasizing that conduct (strategies) can shape market structure and that there is heterogeneity of firms' strategies in an industry, spotlighting strategy as a key element, departing from the rigid industry-centered focus of SCP (Matyjas, 2014). This has significantly contributed to the development of the strategic management field.

One well-known piece of work in strategic management with a strong SCP legacy was developed by Porter in 1980 where he devised five forces emerging from SCP and introduced generic competitive strategies (Tell, 2020). Porter's five forces determine the industry's attractiveness for investment decisions. These five forces are: the entry of new competitors; the threat of substitutes; the bargaining power of buyers; the bargaining power of suppliers; and the competition among existing competitors (Porter, 2004). Based on such an analysis, firms in the industry – or those looking to enter it – can evaluate the industry's appeal and determine the suitable strategic stance for their products in that specific market (Tell, 2020). Within Porter's framework are two primary generic strategies: the cost leadership strategy, in which a firm aims to achieve the lowest production costs to either maintain the highest profit margins given a certain price level in the industry or, alternatively, secure the lowest price position while still preserving margins higher than those of competing firms; and differentiation, where the firm offers unique product features (such as high quality, after-sales service programs, or distinctive product design) that justify a higher price to customers compared to rival products (Porter, 1980, 2004; Tell, 2020). Additionally, Porter suggests that "focus" strategies are available for both options, enabling firms to target specific market segments using either cost leadership or differentiation (Porter, 1980; Tell, 2020).

In essence, Porter's (1980) five forces and generic strategies emphasize an outside-in perspective, suggesting that one should first analyse the attractiveness and condition of the market, and then select a strategy to compete effectively within that market. This approach resembles the so-called "market-based view" (MBV) – i.e., forces in the industry determine its attractiveness and impact the selection of a competitive strategy (Teece et al., 1997; Maier and Remus, 2002; Alnoukari, 2020).

In contrast to the MBV, RBV suggests an inside-out perspective (Tell, 2020). Unlike MBV, which emphasizes the role of industry forces to drive strategies, RBV posits that a firm's internal resources are the forces that drive strategies for gaining a competitive advantage (Maier and Remus, 2002; Soosay et al., 2016). RBV is a dominant theory in strategic management, buttressing the resource approach to developing and sustaining a competitive advantage (Ketchen and Giunipero, 2004; Teece, 2019).

RBV is rooted in the foundational insights developed by Penrose (1959). She emphasized the role of internal resources in shaping a firm's growth trajectory. Specifically, she is concerned with the experience-based accumulation of managerial

resources over time, suggesting that these resources set the ground for managing productive resources that underpin growth possibilities (Penrose, 1959; Tell, 2020).

RBV implies that a firm's bundle of capabilities and resources that are valuable, rare, imperfectly imitable, and not substitutable can lead to developing a sustainable competitive advantage (Barney, 1991; Amit and Schoemaker, 1993). Resources encompass tangible and intangible assets a firm owns or controls (Barney, 1991; Amit and Schoemaker, 1993; Teece, 2019). Capabilities refer to a firm's capacity to deploy its resources, often in combination, through organizational processes, to achieve a desired outcome (Amit and Schoemaker, 1993). RBV posits that a firm's strategic position and potential sustainable competitive advantage depend on how it can manage and utilize its internal resources (Tell, 2020).

Furthermore, Teece (2007) raised pertinent inquiries regarding the inherently static nature of RBV with its primary focus on "internal" resources. Teece (2019) argues that alongside the internal resources, firms need to be able to recognize and utilize other relevant resources that are hitherto external to them, spotlighting the so-called "dynamic capabilities" (please refer to the "Introduction" section for the definition of dynamic capability). Teece (2019) says that RBV falls short in acknowledging the dynamic nature of technological cycles, thus hindering its capacity to fully recognize how certain firms consistently sustain their competitive advantages over time. He introduced a theoretical framework to foster the development of dynamic capabilities, which he thoughtfully subdivided into three interconnected, continuous, or semi-continuous clusters: sensing, seizing, and transforming (Teece, 2019).

In this context, Teece (2019, p.10) articulated the following:

> For applied purposes, dynamic capabilities can usefully be broken down into three primary clusters: (1) identification and assessment of threats, opportunities, and customer needs (sensing); (2) mobilization of resources to address fresh opportunities while capturing value from doing so (seizing); and (3) ongoing organizational renewal (transforming).

Central to Teece's vision is the assertion that dynamic capabilities empower organizations not only to formulate conjectures about emerging technologies, substantiated by relevant adoption, but also to align their organizational assets and activities with the adopted technologies (Teece, 2019). Therefore, a noteworthy strength of his theoretical framework lies in its inclusive nature, effectively encompassing both the decision-making phases of adoption ("sensing" and "seizing") and the pivotal alignment ("transformation") stage. This holistic approach endows Teece's framework with commendable breadth and comprehensiveness, setting it apart from frameworks like Rogers' (2003) "five attributes of innovation" model (relative advantage, complexity, compatibility, observability, and trialability) and the "five stages of the adoption process" (knowledge, persuasion, decision, implementation, and confirmation), which primarily focus on innovation adoption decisions without giving due consideration to alignment requirements.

Furthermore, Geel's (2002) MLP enables the expounding of different levels that can be involved in supply chain actors' transition to Supply Chain 4.0, utilizing their dynamic capabilities. Accordingly, these actors – the Regime – with stable business trajectories seek to sense and seize suitable Supply Chain 4.0 technological solutions tailored by Niche developers (often outside the Regime's boundaries) based on advanced technologies emerged in the landscape. Subsequently, Regime firms undergo an alignment to these seized solutions to unlock their full potential. This account, combining MLP and dynamic capabilities theoretical framework, potentially sheds light on the structure through which firms can import and align with the hitherto external technological resources to gain a competitive advantage.

Furthermore, in the pursuit of the "transformation phase" within Teece's dynamic capabilities framework, this thesis further spotlights the theoretical concept of business-technology alignment from the domains of Information Technology Management and Information Systems. Business-technology alignment underscores establishing a symbiotic relationship between business practices and technology (Duffy, 2002, as cited in De Haes and Van Grembergen, 2009). This notion extends Teece's emphasis on the firm's alignment with technological solutions by positing that this alignment is bilateral. In essence, it encompasses two essential dimensions: aligning the business with technology and aligning technology with the business (Luftman, 2004).

In short, the present thesis adopts Teece's (2019) framework of dynamic capabilities, MLP, and business-technology alignment as its theoretical underpinning. Specifically, this thesis postulates that the technological landscape introduces sweeping technological evolution, engendering the so-called Supply Chain 4.0. To harness the potential of this technological landscape, Regime's supply chains must adapt their dynamic capabilities. Within this overarching framework, the adaptation process encompasses the imperative to sense the opportunities (benefits) and threats (challenges) related to the transition toward Supply Chain 4.0; to seize the relevant transformative technological solutions via Niche actors, and to orchestrate bilateral alignment, for the purpose of undergoing profound and sustained transformation. In this regard, Teece (2019) emphasizes the contextual nature of alignment processes, indicating no universal mechanism for achieving alignment. To respond to this lacuna, this thesis instead focuses on identifying critical factors necessary for successful alignment in the context of the Supply Chain 4.0 transition.

2.4 Intellectual synthesis and thesis framework

The synthesis of pertinent literature serves as the foundation upon which this thesis builds its assumptions. According to this premise, Supply Chain 4.0 is delineated as the application of advanced technologies into the upstream and/or downstream tiers of the supply chain, extending beyond manufacturing boundaries, enabling the technological transformation in the way that supply chains work. This utilization of

advanced technologies within the supply chain context stems from advances in broader digitalization and the technological landscape.

Drawing upon strategic management and MLP, this thesis perceives that the amalgamation of the Regime's supply chain and the Niche technological solution provider (who tailor the solution, based on advanced technologies emerged in the landscape) shapes the supply chain as a strategic organization that pursues the transition to Supply Chain 4.0 and its technologies to enhance competitive advantage. In the context of this thesis, a supply chain, regarded as a strategic organization, is defined as a relatively enduring interfirm cooperative network contributing to the development process of raw materials into distributed products, leveraging technological resources from participants to pursue their goals.

For transition to Supply Chain 4.0, Regime's supply chains must adapt their dynamic capabilities. In pursuit of this objective, the present thesis employs Teece's dynamic capabilities framework, which clusters these capabilities into three interconnected components: sensing, seizing, and transforming.

This thesis enriches this account with a specific focus on the benefits, challenges, and critical factors associated with a transition to Supply Chain 4.0. This approach encompasses two levels of examination, namely the technology and the general, in response to the limited conceptualization of Supply Chain 4.0, attributed to its emerging nature, naturally fluid environment, and limited depth of analyses at the technology level.

At the level of technology, the present thesis delves into the technologies' benefits, challenges, and critical factors. To facilitate this exploration, twelve Supply Chain 4.0 technologies are identified, with four deemed as base technologies (IoT, AI, CC, and BC) due to their pervasiveness, dynamism, and central role in shaping Supply Chain 4.0. This thesis elaborates on the benefits, challenges, and critical factors of these twelve technologies, with a deeper analysis of the foundational quartet.

At the general level, this thesis synthesizes insights derived from Supply Chain 4.0 technologies, comparing them against the context of the case study and literature-driven insights on general Supply Chain 4.0, bolstering the understanding of the subject in a more comprehensive manner and leading to the development of generalized benefits, challenges, and critical factors.

This thesis, in particular, contributes to the "seizing" component by identifying twelve Supply Chain 4.0 technologies that the Regime's supply chain should consider for deployment via technological solutions developed by Niche actors. Subsequently, the present thesis identifies benefits and challenges at the technology and general levels to facilitate the "sensing" phase. Ultimately, this thesis pinpoints critical factors at both the technology and general levels, necessary for the transformation of supply chains to harness the potential of Supply Chain 4.0. At the general level, these critical factors are categorized into three aspects based on the concept of business-technology alignment: those essential for aligning the Regime's supply chain with the Niche technological solutions, those crucial for aligning Niche technological solutions with

the Regime's supply chain, and those vital for both Regime and Niche. Based on the statements above, the thesis framework is developed as follows:

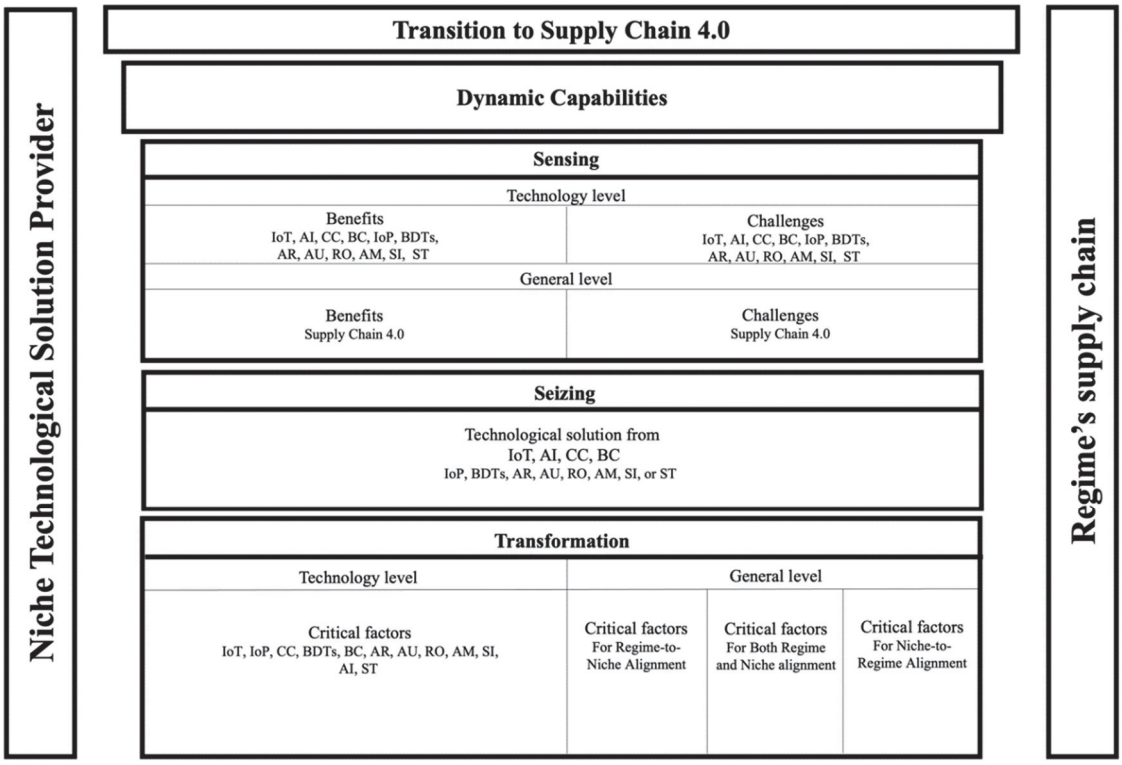

Figure 1: Thesis framework

3. Methodology

This section presents the various methodological choices associated with this thesis. It commences with an overview of this thesis and the studies conducted. Next, it elucidates the rationale and methodological details for each study, followed by a table summarizing the key elements. This section then delves into the applied thesis' methodological approaches and considerations for ensuring research quality. Finally, it concludes by addressing the ethical conduct employed throughout the research process.

3.1 Methodological overview of the thesis

The present thesis is devised to advance the Supply Chain 4.0 domain by investigating the benefits, challenges, and critical factors associated with transitioning to Supply Chain 4.0. The scope of this transition is mainly defined within the Niche-Regime interaction.

The ontological stance of this thesis is primarily subjectivist, emphasizing that reality is developed through the perceptions and interpretations of individuals and groups, which can vary (Hudson and Ozanne, 1988; Don-Solomon and Eke, 2018). This means that the present thesis is based on the author's interpretation of literature and empirical evidence, recognizing that it represents one perspective among many and not the single true facet of reality for the topic in question. In a subset of this thesis (see Study 4), a quantitative method is employed, aligning with objectivism (Antwi and Hamza, 2015), which asserts the existence of a single independent reality, irrespective of individual perceptions (Hudson and Ozanne, 1988).

The combined application of objectivism and subjectivism aligns with the epistemological approach of this thesis: pragmatism. Historically, two of the founders of pragmatism are Charles Sanders Peirce and John Dewey. Peirce defined pragmatism as the belief system prioritizing concepts' practical consequences as the fundamental elements for addressing reality (Peirce, 1905). Dewey (1908) extended this perspective by emphasizing that the practical consequences of ideas and actions should not only be evaluated in terms of immediate outcomes but also in their broader influence on the ongoing development of knowledge. Morgan (2007) has developed a pivotal piece of research on pragmatism in social sciences in the contemporary era. The article presents pragmatism with a focus on the practical utility of research methods, enabling researchers to embrace methodological pluralism, so that methods are chosen that best suit specific research questions and purposes rather than adhering to a single philosophical position (e.g., objectivism and subjectivism). In line with pragmatism, this thesis serves as a practical guide for Regime's supply chains that while hearing the echoes of Supply Chain 4.0, need a guiding index to embark

on such a transition. The present thesis seeks to offer tangible, real-world practical utility by providing a comprehensive framework and actionable insights. However, the aspirations extend beyond immediate practicality. This thesis envisions itself as a catalyst for ongoing discourse and refinement within the field of Supply Chain 4.0. Contributing a framework and practical guidance, it seeks to lay the foundation for future pertinent research development.

Moreover, aligned with pragmatism, the present thesis employs a multimethod approach. In this thesis, four studies are included, comprising one systematic review **(Study 1)**, two conceptual studies **(Study 2 and Study 3)**, and one mixed method study **(Study 4)**. Study 1 led to systematically investigating the available literature related to Supply Chain 4.0 and its technologies. The selection of literature extended to those papers that have been published even without using the term "Supply Chain 4.0", enabling a more comprehensive view of the literature domain in question. The insights obtained suggested several avenues for future research, some of which have guided the inclusion of further studies in this thesis. Specifically, the avenues that guided Studies 2, 3, and 4 suggest more scholarly efforts: A) on the complimentary impact of Supply Chain 4.0 technology with a legacy system (Study 2); B) on the interplay between quantum computers and Supply Chain 4.0 technologies (Study 3); and C) using a mixed-method approach to investigate Supply Chain 4.0 (Study 4).

From the perspective of the Niche-Regime interaction, Studies 2, 3, and 4 approach this interaction from three different angles: Study 2 explores the complementary impact of two technologies – one from the Niche's context, specifically RFID (a subset of IoT), and one from the Regime's context, ERP, a legacy system integral to Regime's supply chains. Study 3 investigates the interplay of nascent technologies, particularly quantum computers, with the established Niche-Regime interaction – Regime's supply chains that have already adopted Niche's BC technology. Study 4 presents an empirical case study of the interaction between a Niche actor, the AI-based system developer, and the Regime's supply chain, including the warehousing company and its ERP developer.

Concerning the benefits, challenges, and critical factors associated with the transition to Supply Chain 4.0, Study 1, based on a systematic review, sheds light on this trio from the general Supply Chain 4.0 perspective and the perspective of eleven out of twelve technologies identified in this thesis. Study 4 addresses this trio with an empirical case, including a Supply Chain 4.0 solution on the general level and AI, SI, and CC on the technology level. The investigation of AI in this study fills the gap related to having excluded this technology from Study 1 (see subsection 3.2 for more details). Study 2 focuses on the benefits of RFID (a subset of IoT) when used in a complementary approach with ERP. Ultimately, Study 3 highlights a challenge and a critical factor related to the utilization of BC in supply chains, an important duo that has been largely neglected in the relevant literature. By this approach, all three research questions for this thesis are addressed with a focus on both general Supply Chain 4.0 and all twelve technologies, with four base ones elaborated more deeply.

3.2 Rationale and methodology for the studies

The rationale and methodological details for each study are elucidated below.

3.2.1 Study 1: A systematic literature review

Study 1 is a systematic review synthesizing intellectual landscape of the relevant literature. It also specifically focuses on identifying the benefits, challenges, and critical factors associated with general Supply Chain 4.0 and eleven technologies: IoT, IoP, CC, BDTs, BC, AR, AU, RO, AM, SI, and ST.

In Study 1, our approach to selecting technologies was guided by a rationale that involved splitting the broad concept of AI into its well-known sub-applications, such as RO and BDTs. This division was made because these sub-applications usually make use of AI properties. As Fenn and Time (2007) have highlighted, technologies can comprise several sub-concepts or sub-applications that find utility in different contexts. In line with this logic, AI is recognized as a dynamic technology with diverse sub-applications applicable to various processes and activities within the supply chain. The chosen approach was necessary for Study 1, since our investigation relied on secondary data sources with a narrowed focus on specific sub-concepts and sub-applications of AI. Treating AI as a single technology could have resulted in overlapping with other technologies like BDTs and RO, potentially leading to their exclusion from the study. However, we chose to avoid such exclusion because even though these technologies are often intertwined with AI applications, they can have distinct benefits, challenges, and critical factors. Therefore, in Study 1, we represented AI by its well-established sub-applications to ensure precision in our results. To complement the insights obtained in Study 1 regarding AI, Study 4 delves into a system with AI at its core.

The systematic review in Study 1 was conducted meticulously, with clear documentation of each step in the process. We used Web of Science (WoS) and Business Source Premier (BSP) databases. The former provided valuable insights from the core discipline of Business Administration and other fields, such as Computer Science. At the same time, the latter focused exclusively on the Business Administration field, capturing relevant business and management articles not covered by the WoS database. We reviewed a total of 1510 abstracts and ultimately included 221 peer-reviewed scientific articles in our final analysis. A thematic technique was employed to extract and categorize the benefits, challenges, and critical factors associated with Supply Chain 4.0 and its technologies under investigation.

3.2.2 Study 2: A conceptual study on ERP and RFID in supply chain

Study 2 focuses on the complementary utilization of RFID, a subset of IoT, with ERP systems, aiming to identify the supply chain benefits associated with their combined use. This investigation of technological implications in a complementary configu-

ration complements Study 1, where technologies were explored separately from one another.

The choice of RFID and ERP for this combinatory study is motivated by the following reasons:

Both RFID and ERP are considered backbone technologies

RFID is a subset of IoT (Fan et al., 2015; Fatorachian and Kazemi, 2021), regarded as the base technology in Supply Chain 4.0. ERP, on the other hand, plays a crucial role in integrating transactions across various business functions and processes (Mabert et al., 2001; Huang and Handfield, 2015), referred to as the "digital nervous system" for businesses (Kashyap, 2011). Given their pervasiveness, technological dynamism, and significant implications, this thesis argues that both ERP and RFID are backbone technologies in supply chains. While IoT, including RFID, is a key component of Supply Chain 4.0, other established technologies, such as ERP systems, are "indispensable" for supply chains (Su and Yang, 2010). Therefore, the interaction between Supply Chain 4.0 technologies such as IoT, once employed, is almost imperative with ERP systems in supply chains, due to their pervasiveness and importance. Hence, the result of this interaction and its impact on supply chain is to be regarded as an interesting scholarly question.

Both ERP and RFID, in isolation, have reasonably well-established bodies of knowledge regarding their impacts on supply chains

These technologies have been reasonably studied in terms of their implications for supply chains, separately. RFID has a well-documented body of knowledge that analyzes its upsides and downsides within the context of supply chain (Musa and Dabo, 2016). Similarly, various studies have investigated the implications of ERP for supply chains (e.g., Hwang and Min, 2015; Aziz et al., 2018). The long-standing status of the literature on these two technologies and the well-established knowledge about their individual behaviors and implications provide a solid foundation for studying their behavior in a complementary setting where RFID and ERP interact. Given the limited focus on the joint examination of supply chain, ERP, and RFID in previous literature, such research can contribute to the relevant domain.

Furthermore, this thesis situates ERP and RFID within the contexts of Regime and Niche, respectively. In this regard, O'Leary (2009) has mapped the development of ERP technology within Gartner's maturity cycle, asserting that ERP was an emerging technology in 1993, underwent adolescence throughout the 1990s, and reached a mature mainstream level by around 2005. In contrast, O'Leary (2009) characterizes RFID as an emerging technology in 2009. Recent perspectives support this classification, considering RFID an emerging technology with demonstrated applications in various scenarios (Ai et al., 2020; Agrahari and Varma, 2021). These observations affirm that ERP aligns with the Regime's context, having been an established main-

stream technology for nearly two decades. Conversely, RFID's status as an emerging technology places it within the Niche's context.

The method employed in Study 2 is conceptual. According to Gilson and Goldberg (2015), a conceptual study focuses on establishing relationships between constructs associated with novelty, and expanding the scope for thinking, relying on logical arguments rather than empirical examination. This emphasis on "newness" distinguishes a conceptual study from a sole literature review, which primarily elaborates on the existing intellectual landscape of research (Gilson and Goldberg, 2015). Given the novel and hypernymic nature of Supply Chain 4.0, exploratory approaches are essential to uncover new perspectives within its incorporated subsets that are yet to be thoroughly discussed. In this context, a conceptual study is valuable for highlighting linkages among technologies and pushing the boundaries of current thinking. Using summarization and integration techniques (Jaakkola, 2020; MacInnis, 2011), such studies facilitate the exploration of technological relationships within the supply chain context. Conceptual studies offer authors unique opportunities to advance the intellectual frontiers, as empirical data do not confine them. These possibilities align well with the domain of Supply Chain 4.0, which is currently in development.

3.2.3 Study 3: A conceptual exploration of the quantum impact on blockchain-based supply chains

Study 3 delves into the interaction between quantum computers, a nascent technology still in its embryonic stages of development, and BC, a base technology in Supply Chain 4.0. This study sheds light on how quantum computing can pose challenges to BC in supply chains (i.e., challenge) and explores the measures required to address this challenge (i.e., critical factor). Consequently, Study 3 reflects on the technological clash between quantum computers and BC while outlining a potential path to form quantum-resistant BC.

Study 1 identifies various challenges and critical factors related to the technologies under consideration. However, there was a notable gap in addressing how different technologies might confront or clash with one another. This contrasts the complementary approach explored in Study 2, where technologies were examined in combination to enhance supply chain benefits. In the context of clashing technologies, it is aimed at understanding how one technology may hinder or disrupt another. Fenn and Time (2007) state that before reaching maturity, emerging technologies can become obsolete with the advent of other technologies.

An example is the case of Kodak, where the advent of digital cameras overshadowed traditional film cameras (for further information on the Kodak case, refer to Lucas and Goh, 2009). While the Kodak case involves two competing technologies, it offers valuable insights into how new technologies can challenge older ones and challenge the businesses invested in them. Study 3 seeks to provide a conceptual

exploration of technological clashes, specifically focusing on challenges and critical factors.

Due to the emerging status of Supply Chain 4.0, challenges pertaining to its technologies are not comprehensively addressed. One of these technologies is BC, on which I exclusively focused in Study 3 from the pool of twelve technologies discussed earlier. The choice of proceeding with a single technology rather than all twelve can be motivated by the argument that a more in-depth understanding of the interplay of technologies and their potential conflicts can be achieved with a narrower focus. If I were to consider several technologies simultaneously, it might require multiple studies to cover them comprehensively, or the depth of analysis would be considerably limited. In this regard, depth is prioritized over breadth to thoroughly explore one case and demonstrate the potential technological clash that could threaten Supply Chain 4.0 within an established Regime-Niche interaction.

Furthermore, BC was selected from the pool of twelve technologies for this study, and the following reasons justify this choice:

BC is a base technology of Supply Chain 4.0

This thesis positions BC as a base technology of Supply Chain 4.0, supported by arguments related to technological dynamism, pervasiveness, and importance, as elaborated earlier. Literature also includes BC as one of the foundational technologies of Supply Chain 4.0 (see, for example, Sobb et al., 2020; Esmaeilian et al., 2020).

BC is gaining in popularity but has yet to reach maturity

BC is gaining in popularity across industries. Since BC implementation involves the transfer of supply chain data to the blocks of this technology, many businesses will eventually have a certain portion of their data (with varying levels of importance and sensitivity) transferred onto BC. Meanwhile, BC, as a technology, has yet to reach maturity and retains certain unresolved downsides that can create issues for businesses (Manners-Bell and Lyon, 2019; Van Hoek et al., 2019).

Regarding BC's maturity, the "Hype Cycle" model is a useful tool for further exploration (see Fenn and Time (2007) for more information on the five stages of the hype cycle). Examining Gartner's BC hype cycle in 2021 (see Litan, 2021), it becomes noticeable that BC has not matured in most aspects. Nevertheless, the hype surrounding the technology has led many businesses and supply chains to adopt it and utilize it for various data types. Therefore, further research into the downsides of BC is necessary to strike a balance between hype and a realistic assessment of this technology. Given that quantum computers can potentially impact the "security by design" characteristic of BC, they can directly affect the security of the data that businesses and supply chains store on this technology (for further information, refer to Paper 3). Therefore, elucidating the interplay between quantum computers and BC, including potential threats and solutions, is essential for businesses harnessing BC.

There is a limited scholarly focus on the relationship between blockchain and quantum computers within supply chain literature

In Study 1, we identified challenges and critical factors related to BC based on a review of the supply chain literature. However, discussions were largely absent regarding the threat posed by quantum computers (i.e., the challenge) and the quantum-resistant BC (i.e., the critical factor). While discussions on the relationship between quantum computers and BC already exist (e.g., Gheorghiu et al., 2017; Campbell, 2019; Fernández-Caramès and Fraga-Lamas, 2020), none of these discussions incorporate the supply chain perspective. Since supply chain is a significant arena for BC implementation, introducing this discourse into the supply chain domain holds considerable importance, and Study 3 aims to fulfill this purpose.

From a methodological standpoint, this study is conceptual. It is underpinned by a vast literature review supporting this study's arguments. Summarization and integration techniques are used to develop conceptual analyses (Jaakkola, 2020; MacInnis, 2011). In this regard, the relevant literature on BC, its role in the supply chain, its security primitives, and quantum computers are elaborated upon. Subsequently, within the frame of the study, these elaborated concepts are integrated to address the study's research question. Since quantum computers are a novel technology developed only to a limited extent, gaining access to insightful empirical material would be challenging. Therefore, secondary data from scientific sources are useful tools to support this research focus within the context of supply chain.

3.2.4 Study 4: A mixed method case study of a transition to Supply Chain 4.0: insights from a Turkish warehouse

Study 4 is the empirical showcase of the transition to Supply Chain 4.0. The design of the case study is divided into four segments: 1) initial phase; 2) preparation for data collection; 3) data collection; 4) data analyses. To develop the case study, Yin (2018) served as a central reference point for developing the initial phase, preparing for data collection, and collecting the relevant data. Data analyses were guided by analytical approaches such as Gioia and statistical analyses.

Initial phase

The initial phase commenced with establishing the rationale for utilizing a case study methodology in Study 4 of the thesis. Building upon the literature-driven insights derived from Studies 1 to 3, which explored the benefits, challenges, and critical factors associated with Supply Chain 4.0 and its technologies, the empirical findings from Study 4 aimed to complement these literature-driven insights, focusing on a real-world case of Supply Chain 4.0 transition. Given the unique contextual elements inherent in each transition case, the case study methodology was deemed appropriate for incorporating these contextual considerations (Gummesson, 2017; Yin, 2018).

Following the selection of the case study method, the subsequent task involved reviewing the literature and formulating research questions – a conventional starting point in case study design (Yin, 2018). This literature review highlighted the warehousing's picking activity and an AI-centered Supply Chain 4.0 solution as signaling key elements to be incorporated into the design of the research questions.

The choice of a technological solution centered on AI has been motivated by the following reasons. First, AI stands out as one of the Supply Chain 4.0 technologies, offering significant promises for supply chains. Second, alongside the benefits, there exists a multitude of challenges in practice that have the potential to impede AI's benefits for businesses (Zhang et al., 2021). Third, the intended enhancements propelled by AI have frequently remained unrealized due to a lack of comprehension regarding the management of AI and its alignment with other applications (Zhang et al., 2021). According to a report, 85% of AI projects failed to deliver the anticipated benefits for businesses (Rayome, 2019). Fourth, the exploration of use cases for AI and advanced technologies within the warehouse context, overall, has not received sufficient attention in research (Mahroof, 2019; Custodio and Machado, 2020). In a similar vein, the preparedness of warehouses to adopt AI represents a notably important area that remains largely overlooked (Mahroof, 2019). Lastly, Study 4 was set to complement the insights obtained in Study 1, delving into a system with AI at its core.

This choice of warehousing process has been driven by the reasons outlined below. With the advent of advanced digitalization and Industry 4.0, warehousing has gained significant importance within the supply chain. Voss (2021) suggests that the growth in product customization under the Industry 4.0 era, along with potential rapid demand fluctuations due to various reasons (e.g., celebrity endorsements leading to increased demand for specific products), has increased the complexity and required efforts for tasks such as picking, packing, shipment, and resource management in warehouses. Consequently, warehouse tasks have expanded, and the management of resources (time and labor) has intensified to improve supply chain efficiency (Voss, 2021). In such a situation, supply chain warehousing must become more efficient and responsive due to the increasing complexity of the process. Order picking is a major activity in warehousing, accounting for a significant portion of the warehouse's total operating cost, ranging from 35% to 75%; inefficiency in this respect can have a crucial impact on the entire supply chain (Coyle et al., 1996; de Koster et al., 2007; Richards, 2017; Stević et al., 2022). Therefore, investigating the potential improvements in efficiency and resource management in the picking activity of warehouses is vital to address the escalating complexity of this supply chain process in the digital era.

Based on the foregoing arguments, three research questions were formulated (please refer to Paper 4). Having established these questions, the subsequent task involved determining whether to pursue a study of a single case or multiple cases. The decision to adopt a single-case study approach was predicated on the aim of conducting an in-depth investigation of a singular case. This approach facilitates the

exploration of intricate nuances and complexities associated with the implementation of an AI-based technological solution within a specific warehouse context, thereby yielding profound insights that might elude a broader, multi-case investigation. Furthermore, concentrating on a single case amplifies the capacity to conduct thorough analyses and develop targeted insights tailored to a distinctive real-case scenario. However, there are also limitations with any single case study. These limitations are touched upon further in this thesis (please refer to sub-section 3.5).

Next, a warehouse was aimed to be selected in Turkey. Several motivating elements were involved in this selection. This thesis is funded by "The Foundation for Baltic and East European Studies" (BEES). Hence, the relevance to Baltic and Eastern Europe is necessary in developing the thesis. In this regard, Turkey is among the countries listed in this geographical area (The Foundation for Baltic and East European Studies, n.d.). Also, Turkey's strategic geographical positioning, acting as a bridge between Europe, Asia, and the Middle East, renders it a crucial hub for international trade and logistics (Özdemir, 2010; Acar et al., 2015; Acar et al., 2020). Given the country's favorable geographic location and its role as a gateway to diverse markets, there is an increasing need to adopt advanced technologies to optimize warehouse operations and bolster competitiveness (Saatçioğlu et al., 2009; Erol et al., 2021). The rising demand for efficient and precise order fulfillment processes underscores the importance of implementing AI technologies into warehouse operations (Cergibozan and Tasan, 2022). The Turkish government has actively encouraged the digitalization of industries, including logistics, through various initiatives and incentives (Duman and Akdemir, 2021). However, Turkey has demonstrated modest progress in transitioning to advanced technologies and Industry 4.0 (Izmen et al., 2020). Therefore, examining the benefits, challenges, and critical success factors associated with an AI-based technological system in a Turkish warehouse aligns with the current state and characteristics of the Turkish context and its journey toward advanced technologies.

With the case criteria determined, Sienzi Lojistik Antrepo ve Dış Tic. Ltd. Şti. (referred to as Sienzi hereafter), a well-established company in the field of warehousing and logistics in Turkey, has been selected as the focal warehouse for further investigation (Please refer to Paper 4 for more information on Sienzi). This selection is also motivated by the willingness of Sienzi for collaboration with the research team, since searching for a willing candidate proved difficult due to the case study research process coinciding with the COVID pandemic. Sienzi embarked on a technological transition journey through an outsourcing arrangement with a Swedish microservices company called Kairos Logic AB (hereafter referred to as Kairos). This transition involves Kairos, a niche actor, and the regime's supply chain. In this case, the scope of the regime's supply chain aligns with Mentzer et al.'s (2001) concept of a "direct supply chain", which encompasses Sienzi specialized in the storage of supplied automotive components, its suppliers, the ERP developer for the warehouse (Select Bilişim Hizmetleri AŞ, referred to as Select hereafter), the distributor, and the

customers who place orders. Active participants from the regime in this transition include Sienzi and Select.

Kairos is the developer of a technological solution centered on AI (referred to as the AI-based system) utilized to improve the order picking activity, primarily through the optimization of pick routing. In essence, customers place their orders with Sienzi, which, through Select's ERP system, transmits these orders to Kairos. Subsequently, Kairos utilizes the AI-based system to develop batch solutions in almost real-time, aimed at optimizing routing, thereby reducing travel time and distance in the picking activity.

The AI-based system integrates two base technologies of Supply Chain 4.0: AI and CC. Also, in the pre-implementation phase, SI is utilized to create a digital twin of the warehouse based on its layout and other relevant information, which is vital for the system's functioning. SI also plays a role in conducting part of the quantitative analyses for Study 4.

Preparation for data collection

In preparation for data collection, the recommendations outlined by Yin (2018) were considered. This involved ensuring that investigators possessed the necessary skills, underwent training specific to the case study, and developed a protocol. Investigators approached data collection with a focus on particular skills, such as being good listeners, asking insightful questions, adapting to unforeseen circumstances, and gaining a thorough understanding of the case. Each investigator has been trained to operate independently, avoiding a rigid formula for inquiry guidance, contributing individually to team discussions for protocol drafting, and making intelligent decisions during data collection process (Yin, 2018). The research team placed a strong emphasis on addressing ethical considerations, resulting in obtaining consent for participation and data sharing before the data collection, as well as confirming confidentiality with case actors afterward (Gregory, 2003).

Regarding protocol development, Yin's four sections were taken into account. Firstly, an overview of the case study was documented, including background information, research questions, rationale, and objectives. Secondly, the roles of interviewees and expected evidence were discussed. Thirdly, questions were designed in accordance with relevant literature (please refer to Paper 4 for more details), linked to the likely source of evidence, and aimed to guide the investigator to remain on track during the data collection. Lastly, the selection of the target journal was considered.

Data collection

After the preparation phase, data collection commenced. Data were gathered from Kairos, Sienzi, and Select through various sources, including eleven semi-structured interviews (9 solo and 2 panel interviews), measurements of order picking, direct observation by two members of the research team at the warehouse site, seven meetings, and communications via WhatsApp and email. Additionally, Kairos provided supplementary documents to offer further insights. This approach aligns with Yin's (2018) principle of collecting data from multiple sources. Furthermore, other data collection principles outlined by Yin (2018) regarding the development of the case study database and the maintenance of a chain of evidence were taken into account. The case study database, comprising data and the researchers' report, was developed, and efforts were made to maintain a clear chain of evidence by highlighting key sections of transcribed text and extracting narrative materials from the database, in line with the questions (Yin, 2018).

Data analyses

The data collection aims to examine the trio of benefits, challenges, and critical factors on both general and technological levels. On the general level, this trio is analyzed regarding the AI-based system as a whole. It targeted to investigate the benefits of the warehousing process due to the implementation of the AI-based system. Additionally, it was targeted to examine the challenges and critical factors that arose during the transition. On the technology level, the focus on the trio narrows down to AI, CC, and SI.

The examined data of benefits, challenges, and critical factors at the general level is reported in Paper 4. The remaining data was utilized in Study 4, outside of Paper 4, where additional facets of the examination at the general level are explored, along with the examination of the trio at the technology level for AI, CC, and SI. Thematic analyses were employed to explore the benefits, challenges, and critical factors associated with these three technologies.

The examined data in Paper 4 are based on three distinct modes: single order-based pick rounds, order batching, and batch-tunnel optimization. The baseline method consists of single order-based pick rounds, involving the initiation from the collection point, followed by item retrieval from shelves for a single order, and concluding with the return of the electrically powered reach truck forklift to the starting point. The order batching mode involves batching the individual orders through the AI-based system to achieve targeted enhancements. The general investigation examines the benefits, challenges, and critical factors in a comparative framework between these two modes, where the former lacks the AI-based system, and the latter incorporates it. In other words, we discerned the resulting benefits stemming from AI-enabled order batching, compared to the conventional single-order picking method used in the warehouse before introducing the AI-based system.

Likewise, we identified challenges and critical factors linked to this transition. Within the batch-tunnel optimization mode, SI techniques were employed to assess the potential reduction in travel distance achievable by introducing a hypothetical tunnel to the warehouse layout.

Paper 4 utilizes a combination of quantitative and qualitative methods. A quantitative approach was adopted, deploying statistical analyses to triangulate results about travel distance and time. Additionally, we evaluated the potential further reduction in distance by simulating the hypothetical tunnel. The quantitative data resulted from measurements, comparing aggregated time and distance between single order-based pick rounds and order batching modes. The comparison results were subjected to statistical testing to determine their significance. The two-sample Kolmogorov-Smirnov test revealed deviations from normal distribution for distance and time variables.

Furthermore, the Mann–Whitney U test, serving as the nonparametric counterpart of the t-test for two independent samples, was employed to compare the order picking and batch optimization groups. The simulation was conducted using software developed by Kairos. The simulation process relied on the digital twin of the warehouse, with two simulations performed: one incorporating the tunnel and one without. Distance measurements were taken for single order-based pick rounds and order batching modes in both scenarios. The resultant batch-driven travel distance in the presence of the tunnel was contrasted with that in its absence, revealing the potential additional distance reduction achievable with the tunnel's implementation. A qualitative approach was employed to bolster the research's comprehensiveness. This qualitative component corroborated findings on travel distance and time while identifying other benefits, challenges, and critical factors. In paper 4, leveraging data structuring techniques, the Gioia approach was adopted to present the qualitative thematic analysis process transparently. The process commenced with extracting "1st order concepts" from raw interview data, which were subsequently refined into "2nd order themes" based on their relevance and characteristics. These themes were further synthesized into "aggregate dimensions", encapsulating benefits, challenges, and critical factors.

The overview of the studies is provided in Table 4.

Table 4: Studies overview

Study	Type	Focus	Positioning in the thesis	Level of analysis	Material
Study 1	Systematic review	- Investigating the Supply Chain 4.0 literature. - Identifying benefits, challenges, and critical factors regarding Supply Chain 4.0, IoT, IoP, CC, BDTs, BC, AR, AU, RO, AM, SI, and ST. - Suggesting avenues for future research.	- Addressing questions 1, 2, and 3 of this thesis. - Guiding the inclusion of other three studies.	Supply chain	221 peer reviewed articles from WoS and BSP databases
Study 2	Conceptual	- Investigating the complementary benefits of RFID (a subset of IoT) and ERP to supply chain.	- Addressing question 1 of this thesis. - Deeper focus on a Supply Chain 4.0 base technology. - Shedding light on complementary impact of Niche-Regime technological interaction.	Supply chain	Literature related to RFID, ERP, and supply chains
Study 3	Conceptual	- Investigating a challenge posed by quantum computers to BC in supply chains. - Investigating the potential measure(s) to address this challenge.	- Addressing questions 2 and 3 of this thesis. - Deeper focus on a Supply Chain 4.0 base technology. - Shedding light on the interplay between a nascent technology in the technological landscape and established Niche-Regime interaction.	Supply chain	Literature related to quantum computers, BC, and supply chain
Study 4	Case study	- Identifying benefits, challenges, and critical factors associated with the AI-based system (a technological solution of Supply Chain 4.0) in the warehouse. - Identifying benefits, challenges, and critical factors related to AI, CC, and SI.	- Addressing questions 1, 2, and 3 of this thesis. - Deeper focus on two of Supply Chain 4.0 base technologies. - Shedding light on Niche-Regime interaction.	Triadic supply chain network (warehouse, warehouse's ERP developer, and AI-based system developer)	Literature, eleven interviews, order picking measurements, direct observation, seven meetings, supplementary documents, and communications via WhatsApp and email

3.3 Research approach

According to Babbie (2009), social research serves three common purposes: exploration, description, and explanation. Exploratory research is well-suited for novel phenomena and, as the name implies, aims to explore the subject; descriptive research seeks to observe the phenomenon and then provide a detailed account of what has been observed; explanatory research delves into the underlying reasons or causal relationships that explain the observed phenomenon (Babbie, 2009).

This thesis is primarily centered on an exploratory approach. While certain Supply Chain 4.0 technologies, such as AM, ST, and SI, emerged before the coinage of Industry 4.0 in 2011, the subject of Supply Chain 4.0 itself is just emerging, limited in conceptualization, and has a long journey ahead. Hence, it is only natural to adopt an exploratory approach, since much "exploration" is required in this thesis for pertinent investigations. The applied exploratory approach expresses the possibility of liberal reasoning on which the foundations of this thesis are built, enabling to advance the frontlines in the Supply Chain 4.0 research domain. The fragmented domain of Supply Chain 4.0 can take a step closer to maturity through exploration.

Next, research is primarily built on three main forms of reasoning: induction, deduction, and abduction (Mantere and Ketokivi, 2013). Inductive reasoning approach is characterized by generalizing from particular observations or evidence (Locke, 2007). Thomas (2006) states that the inductive approach consists of a method in which concepts, themes, or a model are developed primarily through the interpretation of data by a researcher. The deductive approach involves making specific conclusions based on general premises through a logical system (Samuels, 2000; Babbie, 2009; Saunders et al., 2019). *Deductive analysis refers to data analyses that set out to test whether data are consistent with prior assumptions, theories, or hypotheses identified or constructed by an investigator* (Thomas, 2006, p. 238). The abductive approach involves induction and deduction; it encompasses making plausible statements or educated guesses to explain observed phenomena or evidence (Samuels, 2000; Kovács and Spens, 2005). The abductive approach allows for making generalizations by focusing on the individualities of particular situations – i.e., which aspects are specific to the situation, and which are expandable to a broader context, depending on the researcher's knowledge base and past experiences (Kovács and Spens, 2005). Abductive reasoning is underpinned by pragmatism (Morgan, 2007; Shepherd and Sutcliffe, 2011). It can be seen as an approach that emphasizes systematized creativity in research for knowledge building (Kovács and Spens, 2005).

The present thesis is to be considered as a form of abductive reasoning, combining elements of induction and deduction. Inductive reasoning is employed to develop the theoretical framework by merging dynamic capabilities, MLP, and business-technology alignment. Inductive reasoning is also used to identify themes related to benefits, challenges, and critical factors, through data analysis from the empirical evidence and literature. Deductive reasoning is applied by narrowing the theoretical

framework into the specific context of Supply Chain 4.0, detailing it with insights into benefits, challenges, and critical factors. Plausible statements are also incorporated into the thesis to drive the underpinning logic of the research forward and to develop the insights targeted in this thesis. The conceptual development of the thesis is driven by systematized creativity for knowledge building. While certain insights are placed into specific situations, such as contextualized benefits, challenges, and critical factors for Turkey, others are offered for the broader spectrum of supply chains, expanding beyond Turkey.

3.4 Thesis analytical approach

This thesis synthesizes the findings from Studies 1 to 4 into two analytical modules. The first module discusses the trio of benefits, challenges, and critical factors for the twelve Supply Chain 4.0 technologies. This module culminates in the development of Table 5 (Please refer to the "synthesis and discussions" section), which compiles all insights into the trio derived from the studies for all the technologies under consideration.

The second module focuses on identifying and elaborating on the trio at the general Supply Chain 4.0 level. This module begins by synthesizing insights into the Regime-Niche interaction based on the studies. It then delves into identifying themes for the trio by combining insights from the technology level discussed in Module 1 with literature-driven insights for general Supply Chain 4.0 from Study 1. It also incorporates insights related to the AI-based system from Study 4. Afterward, the thesis integrative framework is developed, drawing upon the insights generated in the first and second modules. This framework integrates the synthesized themes and findings, providing a comprehensive view of the transition to Supply Chain 4.0 in relation to the aspects in question. Ultimately, the identified themes related to the trio at the general level and in Study 4 are further examined within the context of Turkey, supported by the relevant literature. This examination helps contextualize the findings and their relevance to the Turkish environment.

The logic behind the thesis' analytical procedure is illustrated in Figure 2 as follows:

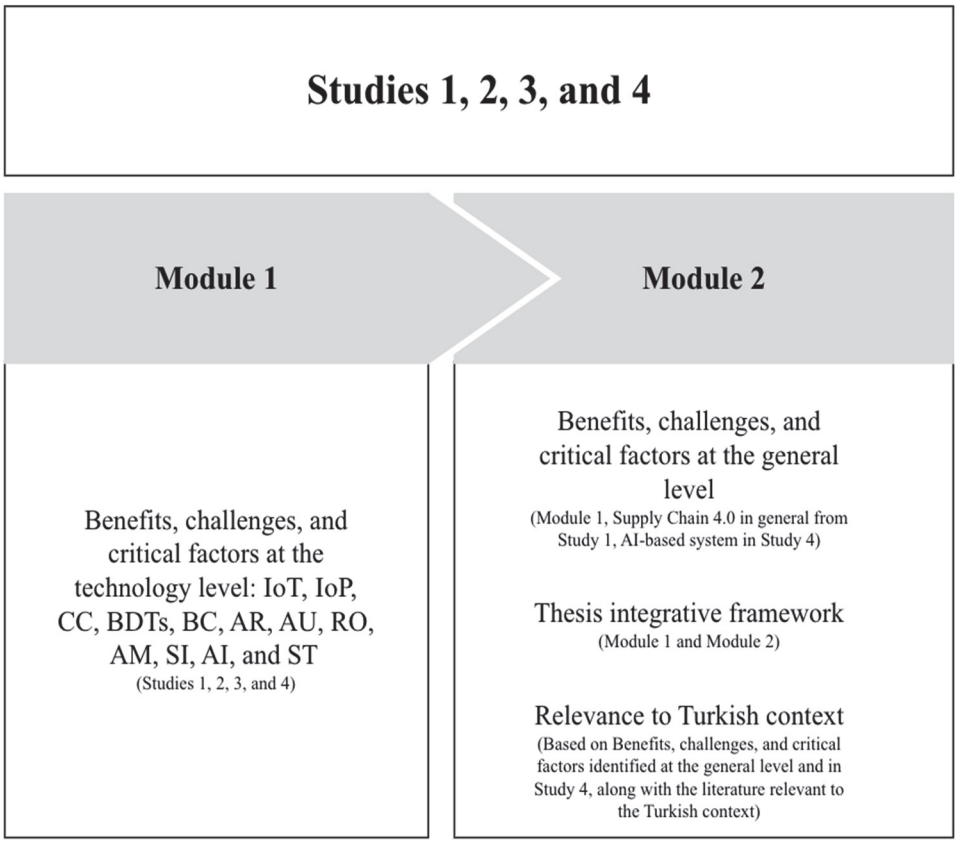

Figure 2: The logic of the thesis' analytical procedure

3.5 Research quality

Regarding the systematic literature review, Denyer and Tranfield's (2009) four principles have been applied to enhance research quality. First, an explicit review process documentation has been provided to ensure transparency. Second, a wide range of relevant literature from two databases has been reviewed to generate comprehensive insights contributing to practice and literature, aligning with the principle of inclusivity. Third, the synthesis has extended beyond the description of evidence, combining elements of reinterpretation while striving to maintain the integrity of the sources to produce novel results. Fourth, the holistic approach of the systematic review equips the results with generalizability to different supply chain contexts and adheres to the heuristic principle. Denyer and Tranfield (2009, p. 681) discussed that heuristic output often guides practitioners *in making progress toward a solution of a problem rather than providing a detailed solution to a specific problem*. They consider this approach more consistent with management and organization studies due to the complexity and diversity of contextual settings. *Heuristic rules will almost always*

require the application of informal judgement or experience to contextualize action (Denyer and Tranfield, 2009, p. 681).

According to Jaakkola (2020), the quality of conceptual studies depends on conceptual clarity, simplicity, logical coherence, and the structure of the study. In this regard, two conceptual studies in this thesis align with these elements. The concepts employed in both studies (RFID, ERP, and supply chain management in one study, and BC, supply chain, and quantum computers in another) have been elaborated, combined with logical straightforwardness and consistency in relation to the studies' questions. The logic is designed to fit well into their respective study's structure, where research questions are problematized, and concepts are elaborated to provide answers.

Furthermore, in line with Creswell's (2014) validity assessment strategies, "peer debriefing" was applied to both conceptual studies, involving external reviewers in the study review process. Additionally, "discrepant information" was included in the conceptual studies to represent distinct perspectives, and "thick descriptions" were aimed at formulating the findings (Creswell, 2014). A substantial amount of secondary data was cited and utilized to thoroughly explore the concepts and establish well-grounded arguments in alignment with the research focus. In this regard, recommendations from Cropanzano (2009) were also considered. Accordingly, the conceptual studies were conducted within domains lacking clear conceptualization, and the connections between constructs (e.g., BC and quantum computers) were carefully established with a strong reliance on existing literature and well-informed arguments (see Cropanzano, 2009).

Study 4 comprises both quantitative and qualitative results. Credibility, confirmability, dependability, and transferability were established regarding the qualitative approach to ensure that the research maintains high quality. Credibility, similar to internal validity, following guidelines by Guba (1981) and Merriam (1998), ensures our instruments accurately measure intended variables, and that results reflect perceived reality. Qualitative and quantitative methods were employed for data collection to develop credibility, with contacts established with the case company before gathering data. "Traveling distance and time reduction" is among the identified benefits measured qualitatively and quantitatively to validate relevant findings. This triangulation confirms the reduction, thereby reinforcing the accuracy of the results. Participant honesty was ensured by selecting genuinely interested individuals and employing iterative questioning. Regular debriefings with the case company were also conducted to clarify misunderstandings and reduce bias. Interview questions derived from existing literature and expert review further secured data credibility. Participants then verified their responses, a crucial step for maintaining study credibility (Guba and Lincoln, 1989).

Confirmability addresses concerns regarding the researcher's biases or predispositions by ensuring that findings are rooted in the perspectives of the participants and the provided data (Guba, 1981). Using data source triangulation and the Gioia

approach, rather than imposing the researcher's interpretations, facilitated a transparent presentation of the respondents' perspectives. Data source triangulation of actors (Kairos, Select, and Sienzi) provided different angles and insights, improving confirmability. Moreover, the limitations of the data collection and analysis methods were evaluated and reported to ensure the confirmability of the research findings further.

Dependability, resembling reliability, assesses whether a study's findings would be consistent if the research were replicated within the same context and methods (Guba, 1981; Babbie, 2009; Oghazi, 2009). To assure dependability in Study 4, the case study design, including methodological choices, was described to facilitate understanding and to ensure reliable findings and replicable results under similar conditions. The data collection and analysis processes were carefully documented, with the aim of reproducibility. With its transparent analytical approach, the Gioia method provided a chain of evidence from raw data to drawn results, facilitating others in replicating the study, thereby strengthening the dependability of the study. Likewise, adherence to the principle of dependability is evident in Study 1 where each step taken during the systematic review is meticulously outlined to facilitate the replication of findings. However, it is important to acknowledge that the primary limitation concerning the dependability of this thesis is associated with two conceptual studies, both of which may need more robust replication power. This limitation is duly recognized and serves the purpose of addressing specific contributions that could potentially encounter challenges within alternative methodological and structural contexts.

Transferability, akin to external validity, refers to the extent to which a study's results can be generalized to other contexts (Merriam, 1998). Studies 1, 2, and 3 encompass more generalizable results than Study 4, partly because of the holistic supply chain perspective employed in them. In Studies 1, 2, and 3, the holistic view enables a broader investigation of supply chains without being restricted to a specific scope of supply chain relationships. Also, the results in these three studies are derived from various secondary sources gathered from diverse disciplines, contributing to the comprehensive development of insights that target a diversified and expanded spectrum of interests. Study 4, conversely, is a single case study centered on a specific scope of relationships, which inherently limits its generalizability into different supply chain setups. The single case study design cannot be effortlessly generalized to a broader population of similar cases despite enabling an in-depth understanding of a specific case.

Consequently, Study 4 offers more detailed and context-specific insights instead of widely generalizable results, similar to those in Studies 1, 2, and 3. Nonetheless, following Firestone (1993) and Lincoln and Guba (1985), transferability was enhanced by providing detailed descriptions of the case study design, Gioia approach, statistical analyses, and the identities of organizations and individuals involved, enabling application to other contexts. Additionally, the number of organizations

involved, their locations, participant numbers, data collection methods, and duration of interview sessions were reported, allowing other researchers to determine the applicability of the findings to different contexts (Cole and Gardner, 1979; Marchionini and Teague, 1987).

Furthermore, Study 4 employs statistical evaluation of quantitative measures through tests. These evaluations assess the significance of differences concerning travel time and distance. A p-value below 0.05 is indicative of statistical significance. It is observed that the reduction in distance demonstrates statistical significance ($p = 0.001$), while the reduction in travel time falls just short of statistical significance ($p = 0.056$). However, it is essential to note that the lack of statistical significance in the reduction of travel time does not diminish the significance of the findings. This is particularly relevant because time and distance are closely interconnected variables, and the p-value for the travel time reduction remains close to the alpha level. The significant outcomes observed add to the potential replicability of the study.

The entirety of the intellectual foundation of this thesis has been crafted through an extensive examination of pertinent literature and empirical evidence. An important objective is to provide comprehensive documentation of the underlying rationale and assumptions that have guided the development of this thesis. The creation of Table 5 and Figure 2 establishes transparency in the process of generating analytical insights. By synthesizing insights derived from diverse sources, including the systematic literature review, the conceptual studies, and the case study, this research endeavors to support the credibility of its findings. The amalgamation of data from multiple sources substantiates the trustworthiness of the thesis' outcomes. The transparent and methodical approach was employed to synthesize these insights and their subsequent integration into an integrative framework, amplifying the dependability and trustworthiness of this research endeavor. Through the synthesis of analyses and discussions from all four studies, the limitation in generalizability found in Study 4 is reasonably addressed when considering the developed themes for the thesis.

3.6 Ethical considerations

One of the key components of any research is the consideration of ethical principles during its development. In this regard, Pimple (2002) emphasizes the importance of being true, fair, and wise as three essential ethical aspects in conducting a study. The following paragraph further explains these three aspects (Pimple, 2002).

Being true involves ensuring that the data collected are reliable and not fabricated or falsified. Being fair focuses on authorship, plagiarism, informed consent from human and animal subjects, and the relationship between researchers and funding sources. Being wise entails considering the implications of the research on society. It involves assessing whether the research will contribute to or harm humanity and the world.

Based on the statements above, this thesis strives for being true by reading all cited literature carefully, aiming to ensure that rephrased or directly quoted text accurately reflects the relevant text of the author(s) in the cited literature. In addition, after the collection and related analyses of the empirical data, results were shared with the case study actors to ensure that findings maintained consistency with what was aimed to be given as the input by them.

Furthermore, this thesis attempts to be fair by ensuring that the data obtained from the literature are appropriately cited in text with full references available in the reference list. The case study actors have each signed a consent letter for participation in the research (templates of consent letters are available in the appendix). Based on the actor's request, a non-disclosure agreement (NDA) has been signed with one of the actors involved in the case study. The sharing of results with the case study actors, following the analysis of empirical data, also safeguards confidentiality. The authorship of the papers and the order of the authors are determined with the approval of those involved. The case study is based in Turkey, a country within the geographic area identified by the research funder as a necessary condition for funding (The Foundation for Baltic and East European Studies, n.d.).

Lastly, wisdom has been the central consideration of this thesis. In this regard, the employed perspectives and implications elaborated in this thesis intend to provide information on how this piece of research has set out to support the world. Noteworthy here is the question regarding the trajectory that some have depicted in relation to nearly full automation of supply chains as the horizon of transition to Supply Chain 4.0, which can significantly reduce the human roles with potentially exacerbated consequences for low-skilled labor (Frey and Osborne, 2017; Ghobakhloo and Fathi, 2019).

4. Summary of papers' results

This section presents a summary of the key results from each of the four papers in this thesis. Papers 1, 2, and 3 fully present the Studies 1, 2, and 3, respectively. Paper 4 covers a part of Study 4. The remaining findings from Study 4 are discussed within the thesis itself, but not included in Paper 4.

4.1 Paper 1: "Industry 4.0 and supply chain performance: A systematic literature review of the benefits, challenges, and critical success factors of 11 core technologies"

This paper investigates the literature status of an established body of knowledge on Supply Chain 4.0 and seeks to identify the pertinent benefits, challenges, and critical factors. First, the literature status of Supply Chain 4.0 is elaborated in terms of the distribution of 221 included papers by year of publication, methodology, journal of publication, and Industry 4.0 in supply chain (Supply Chain 4.0), along with eleven technologies incorporated in this paper.

Findings demonstrate that relevant articles emerged over a span of 16 years, from 2005 to 2021 (refer to Figure 3 in Paper 1). Notably, 166 papers (out of 221) were published in the most recent four years alone, surpassing the combined number of papers published in all preceding years. This suggests a growing academic interest in the subject in recent times. Additionally, the findings indicate that some pertinent technologies emerged and developed before the inception of Industry 4.0 itself. During the early years, papers focused predominantly on technologies such as SI. This outcome suggests that these early technological developments gradually contributed to the emergence of what is now referred to as Industry 4.0, a term formally coined in 2011. In other words, technological advancements over time evolved into a technology-driven revolution.

Next, 221 relevant papers have been published across more than 120 different journals, illustrating the dispersed nature of this subject within academia. This dispersion in publication channels can be attributed to the multi-disciplinary character of Supply Chain 4.0, which often leads scholars to submit their work to journals with diverse foci. The journal with the most publications is the "International Journal of Production Research" which has published 21 out of the 221 included papers. Followed by the "Production Planning & Control" journal, ranking second with 8 papers. For more detailed information, please refer to Table 2 in Paper 1.

Moreover, findings reveal that the empirical method is the dominant approach among all reviewed studies. Papers that employed the empirical method account for

more than half of all included papers. The rest of the papers adopted systematic review, conceptual, and mixed method approaches (see Figure 4 in Paper 1).

Furthermore, Figure 5 in Paper 1 demonstrates the distribution of papers by eleven accounted technologies and general Industry 4.0 in supply chain (Supply Chain 4.0). In this regard, findings show that IoT is the most researched technology followed by BC and AM. Conversely, IoP is the least explored technology followed by ST and AR at the bottom of the list. General Industry 4.0 in supply chain comes after IoT, as the second most explored item in the list. Notwithstanding this, under-researched subareas remain, even within the domain of rather more studied technologies.

Next, Paper 1 sheds light on the benefits, challenges, and critical factors associated with Industry 4.0 and eleven accounted technologies in supply chains. Table 3 in Paper 1 depicts all these benefits, challenges, and critical factors. The most common benefits were integration and optimization, while the most prevalent challenges were centered on cost and human resource issues. Lastly, the most prevalent critical factors were alignment and managerial support.

More specifically, the benefit of "integration" manifests as improvements in information flow and new possibilities for actors' joint operations. "Optimization" benefit refers to improved supply chain processes performances in terms of efficiency, quality, speed etc. Concerning challenges, "cost" mainly relates to high investment requirements for technology acquisition and infrastructure development. And "human resources" challenge is about difficulties of gaining access to relevant specialized skillsets. Ultimately, business-supply chain-technology "alignment" of goals, needs, and strategies is a critical factor. And the "support of management and strategic decision makers" is of significance for the success of Supply Chain 4.0.

Paper 1 offers valuable insights into potential avenues for future research within this field (see Table 4 in Paper 1). The paper indicates that benefits have received more attention than challenges and critical factors, potentially leaving practical gaps in our understanding of the subject. Therefore, one recommended area for future research involves the further exploration of challenges and critical factors. However, given constant technological advances, continued exploration of benefits remains important.

The findings also reveal an imbalance in the depth of scientific discussions across the eleven technologies, with some receiving more attention than others. Even the more explored technologies demonstrate fragmented elaboration at the sub-component and sub-layer levels. This observation calls for future research to address these gaps. Additionally, the literature indicates that categorizations of technologies often overlap and lack a common ground, highlighting the need for scholarly efforts to establish a more comprehensive consensus to develop more concrete insights.

Moreover, the interconnected nature of these technologies can influence the associated benefits, challenges, and critical factors. Technologies continue to grow and new capabilities as well as technologies will emerge. Newer technologies need to work

in harmony with existing legacy systems within businesses. All these imply more research on technological interactions, and this is another avenue among the suggestions for future inquiry.

The scattered publication pattern observed reflects the multidisciplinary nature of this topic and underscores the importance of incorporating diverse perspectives, contexts, and consolidation techniques. It also emphasizes the need for literature reviews that span different disciplines. One specific avenue suggested in Paper 1 encourages more research from a business perspective on Supply Chain 4.0, since many existing studies tend to be directed toward other disciplines, such as computer science.

The predominance of empirical methods in current research highlights the importance of considering alternative methodological approaches, such as conceptual and mixed methods, to develop more comprehensive insights in the future.

Further details are available in Paper 1.

4.2 Paper 2: "RFID and ERP systems in supply chain management"

This conceptual paper aims to elucidate the benefits of ERP and RFID (a subset of IoT) for supply chains. This paper employs the integration school, emphasizing the integration of value-creating supply chain processes, focusing on customer satisfaction. In this regard, supply chain integration is divided into four levels: internal, with suppliers, with customers, and across the chain.

These integration levels correspond to the flow of information and materials within different scopes of the supply chain. "Internal integration" connects separate departments within a single business boundary, synchronizing them into one seamless architecture. "Integration with suppliers" emphasizes establishing connections with suppliers, including data sharing and long-term contracts based on trust and commitment, to foster a win-win relationship. "Integration with customers", as the name implies, focuses on connecting with customers. This relationship is characterized by asymmetric power, leaning toward customers due to their role as the financial injection point into the supply chain, allowing them to request customized services. "Fully integrated supply chain" refers to the complete upstream and downstream integration across multiple supply chain actors.

The combined use of RFID and ERP contributes to integrating the supply chain at all four levels. In brief, RFID enables the generation of information relevant to different firms' internal and external activities, facilitating the tracking and monitoring of physical flows. In this regard, the generated information becomes accessible to different supply chain actors through ERP, as this technology can link information silos in a standardized format. The interactions of the concepts are illustrated in the conceptual model developed in Paper 2 (refer to Figure 1).

For further details, please refer to Paper 2.

4.3 Paper 3: "From Far East to Baltic Sea: Impact of Quantum Computers on Supply Chain Users of Blockchain"

This paper elaborates on the challenge quantum computers pose to BC-based supply chains. The results indicate that sufficiently powerful quantum computers, employing Shor's algorithm, can compromise the core security foundation of BC known as asymmetric (public-key) cryptography. These quantum computers can also employ Grover's algorithm to threaten public BC. The former threat is of particular significance to supply chain users of BC, which allows a cyber attacker to obtain a supply chain user's BC private key. This means an attacker can potentially replace the supply chain actor involved with the BC, thus serving malicious purposes. While this threat is primarily related to BC security, it also poses additional challenges to other BC benefits, such as transparency, traceability, smart contracting, and efficiency.

Furthermore, the findings reveal that quantum computers have already been developed but are not yet powerful enough to pose the aforementioned threats. Various estimates suggest differing timelines for these potential threats. To address this challenge, quantum-resistant security solutions need to be developed. Quantum computers themselves can be part of the solution, but the development and widespread implementation of the security infrastructure for such a solution may take a considerable amount of time. This dual role of quantum computers introduces uncertainty for supply chain decision makers regarding BC investments. For more detailed information, please refer to Paper 3.

The challenge of quantum computers is significant for BC's potential benefits to the supply chain. However, there is a dearth of research in this area, as illustrated by the fact that any mentioning of this issue was absent among the identified challenges of BC in Paper 1.

4.4 Paper 4: "Adoption of AI Based Order Picking in a Warehouse in Turkey: Benefits, Challenges and Critical Success Factors"

Paper 4 presents a case study on an AI-based system, a showcase of a Supply Chain 4.0 technological solution designed to enhance the picking process in warehousing. The investigation aims to identify the benefits, challenges, and critical factors associated with adopting this AI-based system in a Turkish warehouse for picking activities.

The results revealed seven key benefits: *travel distance and time reduction; improved documentation; positive environmental impacts; cost reduction; higher order picking simplicity; higher order picking accuracy, and improved employees' well-being*. Notably, "travel distance and time reduction" emerged from both qualitative data and quantitative statistical analysis. Quantitative data showed a 27.25% reduction in pickers' travel distance and a 22.82% reduction in travel time due to the AI-based

system. Qualitative analysis corroborated these findings. The remaining benefits, as well as all challenges and critical factors, were identified using a qualitative method.

Furthermore, the findings suggested that certain benefits influenced the emergence of other benefits. For example, the "positive environmental impacts" resulted from reduced energy consumption in traveling trucks and their longer lifetime, both of which were consequences of reduced travel distance and time. Additionally, the AI-based system contributed to lower paper consumption, a subset of the "improved documentation" benefit, which further supported the "positive environmental impacts".

Next, the paper includes the Technology-Organization-Environment (TOE) theory to categorize the identified benefits, challenges, and critical factors into technological, internal (organizational), and external (environmental) contexts, which this theory holds as key influencers on business decisions made about adopting technologies. "Cost reduction", "improved documentation", "higher order picking simplicity", and "improved employees' well-being" benefits were primarily associated with the internal context. "Positive environmental impacts" predominantly addressed the external context. "Higher order picking accuracy" and "travel distance and time reduction" fell within internal and external contexts. All seven benefits ultimately resided within the technological context, since they were enabled by a system centered on technological properties.

Moreover, qualitative analysis revealed five critical factors: *strategic alignment; structural alignment*; *operational alignment*; *data privacy*, and *managerial commitment*. The analysis also identified five challenges: *strategic alignment*; *structural alignment*; *operational alignment*; *costs, and resistance to change*. All identified challenges were recognized as critical factors that faced certain complications at their subset levels. Therefore, *strategic alignment, structural alignment, operational alignment, data privacy, managerial commitment, cost considerations, and the degree of resistance/willingness to change* were all considered critical factors. However, "strategic, structural, and operational alignments" faced specific hindrances at their sub-levels. These hindrances, along with "resistance to change" and "costs", were categorized as challenges associated with the AI-based system in the Turkish warehouse. The paper offers a detailed discussion of all critical factors and challenges.

Utilizing simulation, we also found that adding a tunnel in the warehouse would have further reduced traveling distance by 13.91%. Nevertheless, though previously proposed, the tunnel was never built. This rejection was linked to the business adjustment costs (a subset of the emerged "costs" challenge) – i.e., configuring the warehouse layout with respect to the suggested tunnel would be associated with costs. This fact potentially prevented the construction of the tunnel, and thus was a hindrance in achieving a higher benefit in distance and time reduction. We then spotlighted the relationship between the tunnel-building rejection and the "resistance to change" challenge.

From a TOE perspective, the results demonstrated that "strategic, operational, and structural alignments", along with "data privacy" and "costs" corresponded to both internal and external contexts. "Resistance to change" and "managerial commitment" were categorized within the internal context. Regarding the technological context, "strategic, operational, and structural alignments", "data privacy", and "resistance to change" all fell under this category.

For more detailed information, please refer to Paper 4.

5. Synthesis and discussions

In this section, the findings from the thesis and all four studies are synthesized and discussed in relation to the research questions and purposes. It starts by elucidating the trio of benefits, challenges, and critical factors for Supply Chain 4.0 technologies identified in this thesis. This section then discusses the trio with respect to the general Supply Chain 4.0. Subsequently, these findings at technology and general levels are integrated into the thesis framework, leading to an integrative framework. Ultimately, the trio is discussed in the context of Turkey.

5.1 Module 1: Benefits, challenges, and critical factors at the technology level

In this module, benefits, challenges, and critical factors associated with the twelve Supply Chain 4.0 technologies are synthesized. This synthesis is presented in Table 5, encompassing the blend of insights gained from Studies 1, 2, 3, and 4. Insights from Study 1 illuminate the benefits, challenges, and critical factors associated with 11 technologies (excluding AI). Study 2 provides complementary insights into the benefits of RFID, a subset of IoT. Study 3 unfolds insights on complementary challenges and critical factors associated with BC. Study 4 outlines the benefits, challenges, and critical factors associated with AI, CC, and SI.

Based on a systematic review, Study 1 provides a synthesized perspective on supply chain literature in terms of benefits, challenges, and critical factors associated with IoP, IoT, CC, BDT, BC, AR, AU, RO, AM, SI, and ST (see Table 3 in Paper 1). Upon further investigation of the identified aspects, noteworthy insights emerge regarding the impact of technologies on financial performance. In this context, certain technologies, such as AM, are observed to have the potential to contribute to cost reduction in logistics and inventory management, while others like AU and RO can decrease the labor costs. However, it is notable that the adoption of such technologies potentially includes significant setup costs. Moreover, concerning technologies such as IoT and BDT, they show potential in enhancing actors' integration by facilitating connectivity of supply chain information and synchronizing processes. Nonetheless, their implementation necessitates strong collaboration and coordination among these actors.

Study 2 reveals that RFID enables traceability on internal material/product flow, supply status between suppliers and buyers, and overall inventory flow across the chain. This paper also reveals that the data stored on RFID microprocessors can be disseminated to the relevant supply chain actors for data-driven and informed deci-

sion making. By harnessing the power of data-driven decision-making, various processes can be enhanced. For instance, Study 2 reveals that at Level 3 of integration (Integration with customers), RFID tags can store product information during deliveries. This allows customers to verify the compatibility of received items with their actual orders, thereby improving the quality control of deliveries. Lastly, Study 2 unfolds the RFID contribution to create supply chain integration at 4 levels: internal, with supplier, with customer, and across the chain. These four benefits are aligned with four IoT benefits identified in Study 1 – transparency and traceability, awareness and flexibility, performance optimization, and connectivity and integration – corroborating the themes.

Study 3 sheds light on the quantum threat to BC usage in supply chains, driven by two key algorithms: Shor and Grover. When executed on sufficiently powerful quantum computers, these algorithms can undermine BC's security and its associated benefits. BC security relies on two fundamental primitives: hash functions and asymmetric (public-key) cryptography.

The below description aims to illuminate the vital role of these two primitives in enabling BC's data integrity and authenticity, both of which assure the security of BC:

The BC user (hereafter BCU) sends data to the BC. To ensure data integrity and authenticity, BCU uses a hash function to generate a unique hash value of the data. Hash functions play a critical role in this process by taking the arbitrary-sized data and producing a fixed-size hash value that is unique to the original content. Even the smallest change in the data, such as adding a single character, results in a completely different hash value. This property makes it highly effective for ensuring data integrity. By signing this hash value with the private key, which is securely held by BCU, a digital signature is created. The signed data and the hash value are submitted to the BC network and enter a pool of unvalidated data. Depending on the consensus mechanism in use, participants in the BC network validate the data based on predefined rules. The validation process includes verifying the BCU's digital signature using BCU's corresponding public key. This public key is publicly available from trusted sources like a public key repository or the BC itself. Verification is made possible through the mathematical relationship between private and public keys. The public key, part of a cryptographic key pair, ensures data authenticity by confirming that the data's creator had access to the private key at the time of signing. This cryptographic relationship guarantees that only the private key holder could have created the data and its valid digital signature. Thus, the use of the public key in the verification process establishes with a high degree of certainty that the creator of the block is indeed the legitimate holder of the corresponding private key, thereby ensuring data authenticity.

Both hash function and asymmetric cryptography behave as "one-way functions", meaning that performing mathematical operations in one direction is straightforward while reversing them is computationally unfeasible using conventional computers based on binary bits of information. It is easy to compute the public key

from the private key but exceedingly difficult and long to reverse. Similarly, it is straightforward to calculate the hash value (i.e., hash output) from the data input but highly challenging to reverse the process.

However, the emergence of sufficiently powerful quantum computers introduces a quantum threat to BC. Shor's algorithm, when implemented on quantum computers, can potentially reverse the calculation of the private key from the public key in a significantly shorter time frame than conventional computers. This capability could allow a quantum attacker to impersonate an honest BCU, potentially inserting unauthorized data into the BC. Grover's algorithm, on the other hand, can only accelerate brute-force attacks on hash functions to a limited extent. Increasing the size of hash outputs can mitigate this threat. Nonetheless, BC networks that heavily rely on hash functions, such as Bitcoin, remain vulnerable to quantum attacks using Grover's algorithm, since it could enable rapid reconstruction of the entire BC, thereby jeopardizing its integrity.

This quantum threat poses a direct challenge to BC's security, with cascading implications for the broader benefits they offer in supply chains, including robust data traceability and transparency, smart contract functionality, operational efficiency, and decentralization (see Paper 1 for benefits of BC). All these advantages hinge on the foundation of BC security, manifesting in data authentication and integrity. For example, supply chain inventory status stored on the BC by the warehouse is reliably traceable and transparent because the stored data is authenticable. Other supply chain users of BC (e.g., manufacturers) can verify that the block was created only by that specific warehouse. However, in a scenario where an attacker can replace the warehouse user of the BC, the benefits of traceability and transparency are undermined. Furthermore, the disintermediation of supply chain relationships (which can lead to superior efficiency) will be thwarted because the BC will no longer be capable of providing a secure platform for transactions and data.

The solution to this threat lies in the development of quantum-resistant blockchains. Two primary approaches are considered: "post-quantum cryptography" involving mathematical functions, other than conventional ones, which are secure against quantum attacks; or "quantum cryptography" harnessing quantum properties for protection. However, while the former is associated with technical inefficiencies, the latter requires quantum tools that will not be readily accessible in the near future. Besides, building quantum-resistant BC requires infrastructure development, which can take years to complete. The uncertainty surrounding the timeline for the emergence of sufficiently powerful quantum computers adds to the complexity. Estimates vary; some suggest the threat could materialize in the 2020s or beyond. The uncertainty arising from not knowing whether the quantum-resistant solution or the quantum threat will emerge first casts a shadow over the utility of BC in supply chains, underscoring the need for proactive measures to safeguard its security. Quantum threat and quantum-resistant BC present a challenge and a critical factor that have not been spotlighted in Study 1.

Study 4 demonstrates the role of CC, AI, and SI in enabling the AI-based system to optimize the supply chain warehousing process.

The SaaS model is utilized to host the AI algorithm on the cloud, enabling on-demand services in the routing optimization of picking activity in the warehouse case based on the customer's order. The services operate on the cloud without requiring a domestic physical server. George Lijo, the CEO and founder of Kairos, stated that *there is no server sitting here in my office or in Sienzi office*. This can reduce the costs associated with on-site servers for dealing with the information environment, since it allows users to utilize processing power without managing physical machines locally. The cloud-based services enabled scalable data management based on the variation in warehousing customer's request, since it was not bounded by the data scalability limitations of the on-site servers. Furthermore, cloud solution strengthened the supply chain integration as it enabled supply chain actors to make close interactions remotely and as it supported Application Programming Interface (API) establishment for technological interoperability. The four benefits associated with CC align with the systematic review findings in Study 1.

No explicit challenge was observed regarding the utilization of CC. Nonetheless, an important critical factor was observed in relation to the necessity of involved actors' collaboration for establishing the API between Select's ERP system that is already operating in Sienzi and the newly adopted AI-based system. ERP system with warehouse data connected to the Kairos' cloud endpoints for developing API. This involves collaboration among Sienzi, Kairos, and Select in terms of data sharing and technological interoperability. Actors' collaboration was also found among the critical factors of CC in Study 1. Furthermore, as cloud-based information flows take place among the involved supply chain actors, data security and privacy become vital. Empirical evidence however does not show any raised challenge or complication with privacy and security matters, placing them into critical factors. This placement contrasts with the "security" issue of CC, which was categorized into challenges in Study 1. Such a contrast may be attributed to the comprehensive measures taken to ensure private and secure data sharing among the participating actors in Study 4. These measures encompass the establishment of a confidential mechanism, the execution of NDAs, and adherence to regulatory standards. This implies that with proper measures in place, "data security and privacy" is less likely to challenge the utilization of CC in supply chains. Thereby, in this thesis, "data security and privacy" are accounted for as critical factors associated with CC.

Next, Study 4 demonstrates that the utilization of AI in the warehouse picking process results in optimization with manifesting improvements across dimensions of effectiveness and efficiency as well as social and environmental impacts. The AI-driven batch picking has led to a more effective picking process, which is achieved through optimized order picking routes and improved accuracy and simplicity.

The augmentation in order picking effectiveness has concurrently ushered in heightened operational efficiency. This is substantiated by reduced order picking

time, facilitated by the optimized routes and increased accuracy achieved through AI-driven batch picking. Furthermore, adopting batch picking has significantly curtailed the complexity and volume of documentation, thus streamlining operations. This efficiency is fortified by reduced labor costs, stationary expenditures, energy consumption related to truck travel, and the expenses associated with truck maintenance.

In tandem with its efficiency gains, the enhancement in order picking effectiveness has yielded considerable social impact, fostering an environment conducive to improved employee well-being. Reduced paperwork burdens, accelerated picking processes, and decreased error rates, attributable to the reduced operational complexity, collectively contribute to a more favorable working environment.

Driven by the improvements in process efficiency and effectiveness, Study 4 also underscores notable environmental benefits. These include reductions in paper consumption and diminished energy consumption in truck operations, concomitant with an extension of the operational lifespan of the vehicles. These combined advances represent a pivotal shift toward more sustainable warehousing practices, with AI playing a central role in effecting these transformative changes.

Furthermore, three critical factors were observed for AI in Study 4. First, there is a notable dependence on the quality and relevance of the data feed required to drive the AI algorithm. Specifically, optimizing picking routes hinges on a comprehensive pool of data, encompassing historical pick logs and warehouse layout information. The successful utilization of AI is contingent upon the caliber and pertinence of the data supplied. This dependency underscores the importance of information exchange among the participating supply chain entities, which in turn accentuates the emergence of the second critical factor: data privacy and security. The third critical factor observed pertains to technological interoperability. In this case, AI data operates in a cloud environment in close conjunction with the existing ERP system within the warehouse. This interplay between AI, CC and the ERP system underscores the significance of seamless technological integration and harmonious coexistence between them.

There are two notable challenges when it comes to adopting AI in the warehouse operations. One of these challenges pertains to the complex computational aspects involved in designing AI algorithms. These algorithms need to be versatile enough to provide effective and efficient solutions for route optimization across different scales of the problem. This necessitates significant computational and mathematical considerations on the part of the AI-based system developer, which can be quite demanding. The second challenge refers to data structure organization intricacy. AI system relies on intricate and sophisticated ways of organizing and handling the data feed. This complexity arises from the need to represent and process diverse information relevant to routing optimization, such as historical pick logs, customers' orders in hand, and warehouse layouts. Organizing and managing these intricate data structures can be challenging in design, implementation, and maintenance. In light

of these two challenges, Mr. Lijo has stated that *challenges are in computing and need for complex data structures to make AI work.*

The application of SI has empowered the creation of a digital twin of the warehouse, upon which AI algorithms execute optimization procedures. This aligns with the benefit of digital visualization observed in Study 1. Furthermore, SI has also unveiled the potential implication of constructing a tunnel within the warehouse, leading to further reduced travel distances and time. This provides decision-makers with the tools for making informed evaluations regarding the prospective outcomes associated with building the tunnel, aligned with the benefit of assessment of future outcomes identified in Study 1.

Ultimately, the fidelity and precision of the digital twin are intrinsically linked to the quality and comprehensiveness of the information provided by the warehouse regarding its layout. This connection underscores the crucial role of data accuracy, echoing the data input quality critical factor of SI that emerged in Study 1. Ensuring that the digital twin accurately reflects the warehouse's physical configuration necessitates meticulous attention to detail and a commitment to data integrity.

Table 5: Synthesis at the technology level

Supply chain 4.0 technologies	**Themes**		**Study**
Additive Manufacturing (AM)	Benefits	- Optimized supply chain flows	Study 1
		- Product customization	Study 1
		- Improved environmental performance ("green supply chain")	Study 1
		- Integration	Study 1
		- Improved research and development (R&D)	Study 1
	Challenges	- Costs	Study 1
		- Design and production team management	Study 1
		- Restructuring the supply chain	Study 1
		- Availability of printing materials	Study 1
		- Continuous customization and design complications	Study 1
	Critical factors	- Collaborative and integrated product design	Study 1
		- Information platform	Study 1
		- Step-by-step implementation	Study 1
		- Software-printer compliance	Study 1
Artificial Intelligence (AI)	Benefits	- Process optimization	Study 4
	Challenges	- Complex design of AI algorithm	Study 4
		- data structure organization intricacy	Study 4
	Critical factors	- Data feed quality and relevance	Study 4
		- Data privacy and security	Study 4
		- Technological interoperability	Study 4
Augmented Reality (AR)	Benefits	- Customer service	Study 1
		- Improved order picking, routing, and delivery	Study 1
	Challenges	- None were found	Study 1

	Critical factors	- Training and new competences	Study 1
Automation (AU)	Benefits	- Process optimization	Study 1
		- Integration	Study 1
	Challenges	- Cost	Study 1
		- Artificial divide	Study 1
	Critical factors	- Preparation and alignment	Study 1
Big Data Technologies (BDTs)	Benefits	- Awareness and informed decision making	Study 1
		- Reliability	Study 1
		- Information connectivity	Study 1
	Challenges	- Infrastructure and human resources	Study 1
		- Big data governance	Study 1
		- Cybersecurity threat, information leakage, and privacy concerns	Study 1
		- Financial value measurement	Study 1
	Critical factors	- Integration	Study 1
		- Data readability and relevance	Study 1
		- Data modularization and prioritization	Study 1
		- Managerial approach	Study 1
		- Compatibility with governmental laws	Study 1
Blockchain (BC)	Benefits	- Data security	Study 1
		- Data traceability, transparency, and management	Study 1
		- Smart contracting	Study 1
		- Efficiency	Study 1
		- Decentralization	Study 1
	Challenges	- Technical issues	Study 1
		- Human resources	Study 1
		- Governance	Study 1
		- Altering smart contracts	Study 1
		- Quantum Threat	Study 3
	Critical factors	- Preparation and alignment	Study 1
		- Strategic approach and the support of top management	Study 1
		- quantum-resistant blockchains	Study 3
Cloud Computing (CC)	Benefits	- Supply chain integration	Studies 1 & 4
		- On-demand services	Studies 1 & 4
		- Scalability and flexibility	Studies 1 & 4
		- Efficiency	Studies 1 & 4
	Challenges	- Information gap	Study 1
	Critical factors	- Collaborative planning and alignment	Studies 1 & 4
		- Data security and privacy	Studies 1 & 4
Internet of People (IoP)	Benefits	- Customer intelligence and relationship management	Study 1
	Challenges	- Privacy concern	Study 1
	Critical factors	- None were found	Study 1
Internet of Things (IoT)	Benefits	- Performance optimization	Studies 1 & 2
		- Transparency and traceability	Studies 1 & 2
		- Connectivity and integration	Studies 1 & 2

		- Awareness and flexibility	Studies 1 & 2
	Challenges	- Technological infrastructure and human resources	Study 1
		- Control and coordination	Study 1
		- Data security and privacy concern	Study 1
	Critical factors	- IoT alignment	Study 1
		- Top management support	Study 1
		- Performance monitoring	Study 1
		- Proactive IoT	Study 1
Robotics (RO)	Benefits	- Process optimization	Study 1
		- Connectivity	Study 1
	Challenges	- Cost	Study 1
	Critical factors	- Infrastructure	Study 1
Semantic Technologies (ST)	Benefits	- Data linkage and information integration.	Study 1
	Challenges	- None were found	Study 1
	Critical factors	- Ontology and standard	Study 1
Simulation (SI)	Benefits	- Assessment of future outcomes	Studies 1 & 4
		- Assessment of the current system	Study 1
		- Digital visualization	Studies 1 & 4
	Challenges	- Technological infrastructure and human resources	Study 1
		- Information capture	Study 1
	Critical factors	- Data input quality	Studies 1 & 4

5.2 Module 2: Benefits, challenges, and critical factors at the Supply Chain 4.0 level

This thesis adopts the strategic management perspective on supply chains where Regime's supply chains need to adapt their dynamic capabilities for the transition to Supply Chain 4.0 – a technological transformation in the way that supply chains work. Such a transition involves leveraging technological solutions underpinned by a set of technologies, primarily including but not limited to IoT, IoP, CC, BDTs, BC, AR, AU, RO, AM, SI, ST, and AI, often developed by Niche actors. This means that transitioning to Supply Chain 4.0 introduces new actors to the Regime's supply chain. This addition engenders interactions characterized by Regime–Niche technological complementarity, symbiotic alignment, and finite establishments that are subject to change with the ever-evolving technological landscape, as evidenced by the example of quantum computers. The following benefits, challenges, and critical factors are identified to adapt dynamic capabilities, thereby contributing to the components of dynamic capabilities framework, as suggested by Teece's (2019).

Benefits

This thesis presents four benefits of transitioning to Supply Chain 4.0: supply chain transparency; enhanced decision-making; supply chain integration, and supply chain process optimization.

Supply chain transparency

One of the advantages of Supply Chain 4.0 is the enhancement in transparency within the network of the supply chain, a benefit underscored in the literature review presented in Study 1 (Jagtap et al., 2019; Rejeb et al., 2019; Saberi et al., 2019; Mastos et al., 2020; Rebelo et al., 2022). This heightened transparency emerges due to the utilization of Supply Chain 4.0 technologies, such as IoT, IoP, CC, and BC in supply chains. If properly managed, these technologies facilitate the digitization, data collection, and storage of an extensive spectrum of data pertaining to various entities within the supply chain network. These entities encompass a wide array of objects, ranging from machines, raw materials, and supplies to finished products, and extend to encompass transportation means. For example, IoT sensors attached to shipping containers provide real-time location and goods' condition data in logistics. In tandem with this, the scope of data also encompasses human actors, spanning from customers and consumers to social media users and business partners. For instance, by utilizing IoP, an e-commerce company can collect social media data on customer sentiments. Based on the internet, data generation from these multifarious sources begets an extensive reservoir of data, often characterized by its sheer volume and velocity. Study 2 sheds light on how RFID, a subset of IoT, can provide valuable data pertaining to the flow of supplies and products both within and beyond a firm's boundaries, extending its reach to encompass other actors within the supply chain. This RFID-driven data contribution enhances supply chain transparency, adding depth to our understanding of supply chain operations.

Furthermore, through the strategic deployment of technologies, such as BDT, SI, AI, and ST, the deluge of data is effectively transformed into valuable information. For example, a retailer can analyze big data to anticipate demand fluctuations and adjust inventory levels, accordingly minimizing stockouts and overstock situations. This process results in the systematic cultivation of transparency within the supply chain ecosystem, seamlessly followed by traceability. In cases where data reservoir generation and transformation unfold in real-time, the benefits extend beyond mere transparency to encompass trackability. This advanced dimension allows for the real-time monitoring of supply chain processes. This transparency offers a significant boon for the supply chain actors. It illuminates many facets of supply chain operations where these data reservoir generators are strategically employed, providing stakeholders with unparalleled visibility into the intricate processes that constitute the supply chain. This newfound transparency empowers stakeholders with insights and information that were hitherto inaccessible or obscured. It enables comprehensive monitoring of the processes across the supply chain.

Enhanced decision-making

Expanding upon the transparency, Supply Chain 4.0 introduces another notable benefit: enhanced decision-making, an element further emphasized in Study 1 (Ardito et al., 2018; Vieira et al., 2019; Raut et al., 2019; Benzidia et al., 2021; Agrawal

and Narain, 2023). This enhancement materializes in two distinct dimensions: data-driven decision-making and augmentation in information processing capacity. In data-driven decision-making, supply chain actors gain access to a wealth of information, granting them enriched insights into the intricacies of operations. This comprehensive understanding makes them better equipped to make informed decisions. This transformation from intuition-based approaches to data-driven decision-making marks a paradigm shift, leveraging the potential of the digital era. It signifies a departure from traditional methods that often relied on intuition and historical experience – valuable but inherently limited – toward an era where decisions are grounded in empirical evidence. For example, In the realm of IoT, a clothing supply chain can utilize real-time data from IoT sensors to monitor inventory levels, customer foot traffic, and weather conditions. This enables them to make timely decisions, such as adjusting stock levels, staffing, and promotional strategies. In contrast, traditional intuition-based decision-making might rely on past experiences and general assumptions, potentially leading to suboptimal choices and missed opportunities for cost savings and improved customer satisfaction.

In the latter context, technologies such as BDT and AI can increase information processing capacity, thereby reducing uncertainties associated with dynamic environments (Benzidia et al., 2021). SI enables the testing of diverse future scenarios and evaluating their potential outcomes (Vieira et al., 2019). These advanced technological tools effectively contribute to the thinking process, affording decision-makers more time to contemplate and formulate comprehensive decisions. This was also evident in Study 4, where the AI-based system processed routing-related information and devised batching solutions for warehouse operations in almost real-time, all with minimal human intervention. Effectively, the AI-based system assumed a portion of the information processing responsibilities within the warehouse. This, in turn, provided the warehouse workforce with the opportunity to strengthen their cognitive resources in other critical activities, increasing the overall information processing capacity.

Supply chain integration

Another benefit related to Supply Chain 4.0 is supply chain integration, which corresponds to the findings of Study 1 (Frazzon et al., 2019; Tziantopoulos et al., 2019; Frank et al., 2019; Hahn, 2020; Fatorachian and Kazemi, 2021). As stated earlier, supply chain integration denotes the ability of supply chain actors to conduct supply chain activities jointly (Forslund and Jonsson, 2007 & 2009). Within the domain of Supply Chain 4.0, the exchange of data among actors, whether in real-time or otherwise, bolsters connectivity and fosters information sharing in the supply chain network. This facilitates the integration of information flows, enabling them to react promptly to evolving market dynamics. Study 2 further corroborates the supply chain integration by highlighting the pivotal roles played by technologies such as RFID (a

subset of IoT) and ERP systems in generating and transmitting critical information, thereby contributing to internal and supply chain-level integration.

Moreover, the transparency and transformation of data into invaluable insights – facilitated by technologies like AI and BDT – are frequently driven by data reservoirs sourced from diverse actors within the supply chain. The resulting insights transcend the boundaries of individual firms, readily usable and shareable by various supply chain actors. This synergy reinforces integration and holds the potential to extend into joint decision-making processes, supporting the enhancement of the supply chain's agility and resilience. In essence, within the context of Supply Chain 4.0, supply chain integration represents a fundamental shift toward heightened connectivity, extensive information sharing, the synergy by insight-driven processes, and the potential for joint decision-making.

Supply chain process optimization

The final benefit within the domain of Supply Chain 4.0 centers on the optimization of supply chain processes, as emphasized in Study 1 (Krykavskyy et al., 2019; Frazzon et al., 2019; Ghadge et al., 2020; Sharma et al., 2021; Eslami et al., 2021). In this thesis, optimization refers to the systematic enhancement of how supply chain actors execute their processes and activities to attain specific objectives. These objectives can vary, contingent on the contextual particulars, such as heightened efficiency, productivity, quality, sustainability, flexibility, and agility. Two primary factors condition this optimization. First, it is nurtured by transparency, enhanced decision-making, and integration benefits previously expounded in relation to Supply Chain 4.0. When actors can transparently monitor, trace, and track supply chain processes, bolster their decision-making, and engage in heightened integration, the potential for systematic process improvement becomes manifest. For instance, within the ambit of IoT-driven smart transportation systems, data streams from GPS systems, real-time traffic updates, and weather forecasts coalesce to empower transportation actors to optimize routes continuously. These dynamic adjustments, made in response to traffic conditions and weather forecasts, yield minimized fuel consumption, streamlined routes, and more efficient delivery schedules. This results in substantial cost savings and a reduced environmental footprint. Or AM provides supply chains with transparent insights into material and energy requirements for manufacturing; this transparency leads to optimized supply chain material flows, reduced environmental impact, lower logistics and inventory levels (Baumers et al., 2013; Verboeket and Krikke, 2019).

Secondly, Supply Chain 4.0 technologies themselves contribute directly to process optimization. IoT devices, for instance, can incorporate actuators or similar tools that enable embedded objects to perform certain actions autonomously (Molka-Danielsen et al., 2018). These actuators respond to real-time data, augmenting the autonomy of IoT-connected objects. Consider the case of a smart thermostat in a supply chain warehouse; it autonomously adjusts temperature settings in response to

changing environmental conditions, ensuring optimal product storage conditions. In electronics manufacturing, AU can automate printed circuit board inspections, swiftly identifying defects such as soldering issues, reducing manual checks, and ensuring quality control consistency. AR tools like smart glasses and wearable devices enhance the precision and speed of tasks such as order picking and delivery (Agrawal and Narain, 2023). RO can be employed in an automotive manufacturing plant for tasks like welding. Industrial robots equipped with welding arms can precisely and consistently weld together components of a vehicle's chassis. These robots work tirelessly without fatigue, ensuring uniform weld quality across numerous automobiles. AI-driven systems can continuously learn from data, adapting and fine-tuning activities. The role of AI in optimization was also evident in Study 4. The AI-based system reduced travel time and distance. These improvements led to cost reductions in energy expenditure for truck traveling, truck maintenance, and labor. Furthermore, the AI-based system demonstrated positive environmental implications, reducing fuel consumption while increasing the truck's lifespan.

Challenges

Transition to Supply Chain 4.0 presents a range of formidable challenges, encompassing: high costs; the scarcity of requisite skillsets; concerns relating to security and privacy; complexity surrounding infrastructure development; the intricacies of coordination, and inherent complexities within the technologies themselves.

High costs

In Study 1, high costs emerged as one of the most frequently emphasized challenges within the reviewed literature in the context of Supply Chain 4.0. This challenge encompasses several facets, one of which pertains to substantial upfront investment requirements (e.g., Gružauskas et al., 2018; Sharma et al., 2021). The transition to Supply Chain 4.0 can demand significant initial capital for various purposes, including the acquisition of technological equipment. For example, technologies like IoT (de Vass et al., 2021), AM, or its required material (Holmström et al., 2016), can entail considerable acquisition expenses. Another dimension of this challenge relates to infrastructure development costs (e.g., Ghadge et al., 2020). These costs may encompass expenses associated with adapting business infrastructure to accommodate Supply Chain 4.0 technologies. For instance, companies might be required to invest in physical transformations of their facilities to optimize processes, as illustrated in Study 4. In this case, the warehouse could build an additional tunnel to reduce further travel distances in the routing activity of its picking, an enhancement driven by the AI-based system. Infrastructure development costs can also extend to deploying tools for data processing, protection, and storage.

Additionally, there are continuous costs associated with workforce hiring and training. As businesses embrace advanced technologies, they must allocate resources to ensure that their employees possess the necessary proficiency in the dynamic

environment of Supply Chain 4.0. Another potential cost to consider is maintenance expenses. A practical example of maintenance costs can be seen in Study 4, where these expenses were factored into the monthly subscription fee established by Kairos. In general, while the transition to Supply Chain 4.0 brings the promise of long-term cost savings, there are certain cost-incurred characteristics associated with this transition that need to be considered.

Scarcity of requisite skillsets

In the landscape of Supply Chain 4.0, a formidable challenge emerges in the form of the scarcity of requisite skillsets, as evident in the reviewed literature in Study 1 (Luthra and Mangla, 2018; Martínez-Olvera and Mora-Vargas, 2019; Sharma et al., 2021). The transition to Supply Chain 4.0 is often associated with new business models and innovative approaches to value creation (Luthra and Mangla, 2018; Martínez-Olvera and Mora-Vargas, 2019; Kohtamäki et al., 2019). These changes in supply chain practices, driven by Supply Chain 4.0 technologies and data-driven decision-making, have substantially reshaped the skills landscape. While some traditional Regime's supply chain competencies remain pertinent, they now coexist with an escalating demand for expertise in Niche technologies such as AI, BDT, and IoT. These scarce skillsets are significant for unlocking the potential in transitioning to Supply Chain 4.0. For instance, considering data analytics, where the requisite skillset extends to prioritizing data-driven insights; this heightened complexity requires data science skillsets to develop sophisticated algorithms for effective prioritization (Luthra and Mangla, 2018).

Additionally, the imperative of establishing interoperability between new technologies and existing systems underscores the demand for complex and scarce skillsets in orchestrating the technical environment of Supply Chain 4.0 (Sharma et al., 2021). This was evident in Study 4, where Select encountered difficulties in replacing the lost software engineers, resulting in complications with the integration of ERP and the AI-based system. Furthermore, the economic dimension introduces its own set of challenges. Calculating the return on investment (ROI) for Supply Chain 4.0 solutions within the Regime's supply chain context is multifaceted, necessitating a high level of proficiency in both technical and business domains (Luthra and Mangla, 2018). The resulting skillset shortages initiate a competitive race among organizations, intensifying the complexity of recruitment processes.

Security and privacy concerns

The next challenge revolves around security and privacy concerns, a topic emphasized in Study 1's literature review (Mondal et al., 2019; Kamble et al., 2019; Birkel et al., 2019; Ghadge et al., 2020; Jabbour et al., 2020; Sobb et al., 2020; Agrawal and Narain, 2023). Supply Chain 4.0, with its expansive data environment, becomes an enticing target for cybersecurity risks (Ghadge et al., 2020). The heightened reliance on the internet and the multi-actor nature of Supply Chain 4.0, compounded by its underlying technologies, create a fertile ground for potential security threats (Sobb et

al., 2020). The integration of technologies within the supply chain network renders it vulnerable to virtual-world threats, with the scale of the network and the proliferation of interfaces directly amplifying the potential attack surface and the associated risk of cyberattacks (Birkel et al., 2019). In network-based systems, security confronts a spectrum of challenges, including the ever-present risks of data tampering, unauthorized access, and possible network disruptions (Navajo et al., 2010, as cited in Kamble et al., 2019). Furthermore, the emergence of forthcoming technologies can pose security threats to technologies that are presently considered secure, such as BC, as explained in Study 3. Additionally, concerns arise regarding the safeguarding of confidential data by actors, further contributing to the intricacies of Supply Chain 4.0 (Agrawal et al., 2019, as cited in Agrawal and Narain, 2023). Emerging technologies like BDT and IoT, integral to managing diverse supply chain data, introduce concerns related to the privacy and confidentiality of information (Mondal et al., 2019; Jabbour et al., 2020).

Infrastructure development complexities

The fourth significant challenge pertains to the complexities of infrastructure development, a challenge that has been notably underscored in the literature reviewed in Study 1. This complexity is intertwined with several elements that collectively contribute to the intricate nature of building the necessary infrastructure for the transition to Supply Chain 4.0. One facet of this challenge revolves around the availability of financial resources and the scarcity of requisite skillsets, both of which have been explored in-depth previously. The limitations imposed by these elements significantly amplify the overall complexities involved in infrastructure development. Another dimension of complexity arises from the limitations and speed constraints of internet infrastructure (Gravili et al., 2018; Gausdal et al., 2018; Kamble et al., 2019; Jabbour et al., 2020). Adequate internet access is a pivotal requirement for all stakeholders engaged in Supply Chain 4.0, mainly when dealing with data-intensive technologies like IoT in real-time environments. Unfortunately, this level of connectivity may not be uniformly accessible throughout the supply chain, especially for upstream actors such as farmers in less developed regions (Kamble et al., 2019). Technology-specific complexities further compound the infrastructure development challenge, encompassing aspects like security and control mechanism development, scalability, and the suitability of the hosting context for technology adoption (Gessner et al., 2007; Roussos, 2008; Kache and Seuring, 2017; Min, 2019). A prime example of this complexity can be found in Study 3, which taps into the time-consuming and intricate task of establishing quantum-resistant cryptography infrastructure for BC security. The development of the Regime's infrastructure, another facet of this multifaceted challenge, is also not always straightforward. For example, modifying the existing facility layout to improve the benefits gained from the technological solution, as suggested in Study 4, can potentially disrupt operational processes. Lastly, the Regime's cultural and social barriers emerge as formidable obstacles in developing the requisite

infrastructure to host Supply Chain 4.0 technologies within the supply chain context. These barriers manifest in different appearances, such as resistance to change, apprehension about potential job displacement, mental stress resulting from adding new tasks to established routines, and a general distrust in emerging technologies (Birkel et al., 2019). The complexity of these barriers is exacerbated by the intricate web of multiple actors within the Regime's supply chain, where cultural and social factors can manifest across various entities, amplifying the overall challenge. In Study 4, elements of limited enthusiasm toward implementing changes were noted in Sienzi. This reluctance to change was linked to initial concerns about losing freedom in picking and to the stress of alterations in daily tasks due to the construction of the tunnel. Moreover, an added layer of complexity stemming from social and cultural barriers, particularly resistance to change, lies in the intricacy of pinpointing the precise motivations behind such resistance. Individuals who exhibit resistance may not consistently articulate their underlying reasons, making it challenging to discern the exact factors at play.

Intricacies of coordination in Supply Chain 4.0

The fifth challenge revolves around the intricacies of coordination in Supply Chain 4.0. The challenges associated with the intricacies of coordination in Supply Chain 4.0 are multifaceted, as highlighted in the reviewed literature (Holmström et al., 2016; Kache and Seuring, 2017; Brinch et al., 2018; Sobb et al., 2020; de Vass et al., 2021). One of these facets pertains to data coordination intricacy in Supply Chain 4.0. Effective data flow is paramount for harnessing the potential of Supply Chain technologies. Coordinating the seamless flow of data can present significant complexity, whether it involves collaborative 3D model design in AM (Holmström et al., 2016), achieving supply chain-wide real-time data sharing for IoT-enabled operations (de Vass et al., 2021), or governing, prioritizing, and sharing data related to BDT (Kache and Seuring, 2017; Brinch et al., 2018). The regime's privacy and security concerns can also aggravate the data coordination challenges, since they can disrupt data sharing. Another subset of this challenge lies in the absence of common standards among the myriad of fragmented systems employed across supply chains, which can hamper interoperability (Kache and Seuring, 2017; Sobb et al., 2020; de Vass et al., 2021). This was evident in Study 4, where Select and Kairos had to develop a new API to establish interoperability between their technological systems, resulting at first in a struggle with technological adaptation. Supply Chain 4.0 technologies, in conjunction with older legacy systems, often employ a multitude of diverse standards, necessitating complex data transformation and mapping processes. Besides, implementing changes in existing systems can trigger operational disruptions, further exacerbating coordination challenges. The latter spotlights another facet – the intricacies of coordinating Regime's business operations – to effectively leverage Supply Chain 4.0 technologies. As observed in Study 4, this aspect can become convoluted, with issues such as ineffective inter-actor communication, incoherent planning, and shifts in

documentation approaches. Intricacies of coordinating business operations can manifest in other ways, including cultural and behavioral coordination and compliance with regulatory requirements.

Inherent complexities within the technologies themselves

The final challenge is associated with the inherent complexities within the technologies themselves. Supply chain 4.0 is built upon a framework of advanced technologies and the internet, forming an essential foundation for the disruptive changes envisaged by this paradigm shift. This profound dependence on these technological artifacts introduces a challenge that strikes at the very core of its foundational enablers. This reliance is vulnerable to various factors. Firstly, the internet, a cornerstone of Supply Chain 4.0, can experience disruptions or outages, potentially impeding smooth operation (de Vass et al., 2021).

Furthermore, the rapid pace of technological innovation introduces the risk of Supply Chain 4.0 technologies becoming obsolete and supplanted by more capable alternatives (de Vass et al., 2021). As an illustrative instance, the shift from typewriters to personal computers exemplifies this dynamic technological landscape. This dynamic landscape, as illustrated in Study 3 concerning the interplay between quantum computing and BC, can extend to the disruption of established technological paradigms by nascent technologies. Additionally, potential glitches and inherent limitations can impede the effectiveness of these technologies. For example, while highly secure and immutable, BC technology can pose challenges when data alterations are necessary (Esmaeilian et al., 2020), such as for error correction to ensure regulatory compliance. Another instance is evident in AM, where constraints related to the variety of available printing materials can restrict the scope of manufacturing possibilities (Hohn and Durach, 2021).

Critical factors

The critical factors center around business-technology alignment. Within the context of this thesis, critical factors are further delineated into three alignment aspects: critical factors for Regime-to-Niche alignment; critical factors for Niche-to-Regime alignment; and critical factors for both Regime and Niche alignment.

Critical factors for Regime-to-Niche alignment

These critical factors refer to those elements essential for aligning the Regime's supply chain with Niche technological solutions. These critical factors are Supply chain process reengineering, data management, and management commitment.

Supply chain process reengineering

A pivotal element pertains to the reengineering of supply chain processes, as also highlighted in the literature in Study 1 (Patrucco et al., 2020; Sharma et al., 2021; and Ali and Aboelmaged, 2022). This process embodies a redesign aimed at aligning supply chains with the transformative capabilities of Supply Chain 4.0. This encom-

passes physical transformations, as evidenced in the case of Study 4, where modifications to the warehouse layout, including the addition of a tunnel, held the promise of significantly reducing travel distances. Furthermore, supply chain process reengineering extends its reach to accommodate and adapt to the altered landscape of Supply Chain 4.0-enabled business approaches. For instance, in Study 4, the adoption of the AI-based system triggered a shift in picking methodologies, transitioning from single order picking to batch picking. While this transformation promised efficiency gains, it also introduced complexities in sorting activity, necessitating additional time for batched item sorting to meet individual customer requirements. To address the issue, Sienzi implemented a new labeling approach where products are labeled while picking, rather than using the traditional method of labeling at the collecting area. For successful navigation of transitions under Supply Chain 4.0, operating businesses within the supply chain must engage in thorough pre-implementation assessments. Such assessments provide a comprehensive understanding of the existing business environment, forming the basis for collaborative planning with Niche solution developers. These joint efforts are essential in identifying realistic adaptation avenues within the context of Supply Chain 4.0.

Moreover, the critical facet of supply chain process reengineering involves the reconfiguration of information flow dynamics. As highlighted in Study 1, the establishment of robust mechanisms for information exchange among supply chain actors becomes imperative when leveraging technologies like CC, BC, and BDT (Jede and Teuteberg, 2015; Kache and Seuring, 2017; Molka-Danielsen et al., 2018; Saberi et al., 2019). This necessitates the realignment of information flow channels to facilitate coordinated inter-actor data sharing and information dissemination. Study 4 further exemplifies this reconfiguration, where Sienzi and Select are directed into the cloud-based information exchange mechanism to share customers' orders with Kairos in Sweden, thereby transforming the supply chain's linear relationships into non-linear ones.

Data management

The second element refers to data management. As evidenced in Module 1, the significance of data input quality and relevance becomes apparent, especially concerning technologies like AI, SI, and BDT. This reliance underscores the necessity for a collaborative mechanism not only for information exchange but also for high-quality data input. Effective data management can extend to the insight distribution phase. For instance, the resulting insights from BDTs need to be directed to the relevant actors in the supply chains for pertinent applications.

Management commitment

The last critical factor refers to management commitment, as emphasized in Study 4. Several pieces of research in Study 1 have also highlighted this element (Birkel et al., 2019; Luthra et al., 2020; Bamel and Bamel, 2021; Sharma et al., 2021). Management commitment is an indispensable cornerstone for the effective transition to Supply

Chain 4.0. It signifies strong support from top-level leadership, including the C-suite and board members, in embracing the transition journey. This commitment is not just vocal but is substantiated through resource allocation in terms of finances and skillsets. By earmarking budgetary provisions and ensuring the availability of skilled personnel, management sends a clear message that Supply Chain 4.0 is a strategic priority.

Furthermore, management commitment extends to proactive engagement in change management efforts. This entails fostering a culture of openness to change, addressing potential resistance, and ensuring that all stakeholders understand the overarching vision of the transition. In essence, management commitment sets the tone for the entire transition approach to Supply Chain 4.0, demonstrating that the journey is not merely a trend but a fundamental shift in how the supply chain operates. As Supply Chain 4.0 brings about new challenges and uncertainties, committed leadership actively assesses potential risks and formulates strategies to mitigate them. This proactive stance ensures a smoother transition to digital processes and minimizes disruptions. Instead of pursuing short-term gains, management commitment underscores the dedication to continuous improvement along this path. It also emphasizes clear communication of strategic objectives and the establishment of key performance indicators (KPIs) to measure success. Therefore, management commitment provides the vision, resources, and guidance needed to navigate the complexities of Supply Chain 4.0 and thrive in the digital transformation era.

Critical factors for Niche-to-Regime alignment

These critical factors refer to the elements essential for aligning Niche technological solution providers with the Regime's supply chain. These critical factors include: understanding of the Regime's context by the technological solution provider; customization of technological design and solutions, and technological maintenance.

Understanding of the Regime's context by the technological solution provider

One critical factor revolves around a profound understanding of the Regime's context by the technological solution provider. To effectively align technology with the intricate fabric of supply chains, cultivating a deep comprehension of the specific requirements and nuances inherent to the targeted Regime's supply chain scope is paramount. This entails delving into a multifaceted exploration, encompassing the discernment of Regime actors' objectives for embracing the Supply Chain 4.0 transition, coupled with an astute grasp of the operational dynamics. This includes meticulous considerations such as supply chain structure, customer demands' cadence, and the competitive landscape's ever-evolving contours. Each actor within the supply chain operates within a unique and distinctive environment, and it is incumbent upon technological solution to harmonize seamlessly with contextual intricacies. A vivid illustration of this principle unfolded in the course of Study 4, where the pivotal role of comprehending the warehouse's objectives and requisites came to the fore during the adoption of the AI-based system. Kairos embarked on a

journey to fathom the intricacies of the warehouse's dynamics, encompassing factors such as the frequency and setup of customer orders, facility layout planning, existing technological environment, and adherence to regulatory frameworks. This understanding served as the foundational bedrock upon which the AI-based system was designed and tailored to fit the contours of the warehouse. Nonetheless, it is worth noting that despite these efforts, the emergence of complexities in sorting activity partly reflects Kairos' limited understanding of Sienzi's operational procedure, which they could have foreseen and proactively contributed to addressing.

Customization of technological design and solutions

Another critical factor pertains to the customization of technological design and solutions. Once a comprehensive understanding of the business context is achieved, tailored technological solutions can be devised to address contextual specificities. For example, the analytics of big data involves their transformation into relevant information to the context, that is intelligible and actionable, complemented by visualizations, to derive valuable insights (Molka-Danielsen et al., 2018). This entails the meticulous design of technological systems to meet the unique requirements of the targeted supply chain context. In Study 1, several pieces of literature underscored the significance of design in harnessing technologies to realize the intended benefits of transition to advanced technologies and Supply Chain 4.0 (Holmström et al., 2016; Molka-Danielsen et al., 2018; Bienhaus and Haddud, 2018; Yang et al., 2021). This design process encompasses the effective orchestration of various technologies within a technological solution. Scalability is another integral facet associated with Supply Chain 4.0 (Jede and Teuteberg, 2015; Shahzad et al., 2020; Agrawal and Narain, 2023) and must be integrated into the technological design to accommodate the dynamic scale of operations. In Study 4, the AI-based system's batch optimization solution was designed and customized, integrating technologies such as AI, CC, and SI, while carefully considering the warehouse layout and historical pick logs.

Technological maintenance

Technological maintenance is another critical factor, ensuring the long-term effectiveness of Supply Chain 4.0 technological solutions in supply chains. It encompasses a strategic approach to sustaining the technological solutions, including regular maintenance routines to prevent disruptions, upkeep system performance levels, and maintain robust cybersecurity. Compliance with industry regulations is also paramount. Overall, technological maintenance is essential to ensure the technological solution remains a strategic asset in the supply chain realm. In essence, technological maintenance is vital for aligning technologies with the dynamic requirements of Supply Chain 4.0. It guarantees the reliability, efficiency, and security of technological solution, safeguarding their strategic value within supply chains. Study 4 highlights the relevance of this critical factor, as it elucidates the provision of post-implementation maintenance services by the AI-based system developer, included in its monthly subscription fee.

Critical factors for Both Regime and Niche alignment

Several critical factors are mutual, integral to both Regime and Niche. These critical factors are the provision of requisite skillsets and knowledge, financial planning and investment strategy, data privacy and security considerations, technological infrastructure development and interoperability, and supply chain collaboration.

Provision of requisite skillsets and knowledge

One critical factor is the provision of requisite skillsets and knowledge, an element underscored in the reviewed literature of Study 1 (Frazzon et al., 2019; Frederico et al., 2019; Ghadge et al., 2020). These skillsets encompass a broad spectrum of expertise, spanning areas such as data science, change management, cybersecurity, and more. The provision of skillsets and knowledge involves several dimensions. Firstly, it necessitates an assessment of the existing competencies within the current workforce, encompassing both Regime and Niche actors. Another dimension involves acquiring the necessary skillsets and knowledge from external sources where needed, whether by recruiting new talent or outsourcing specific tasks. The imperative of continuous upskilling becomes evident when considering the ever-evolving dynamics of Supply Chain 4.0, as illuminated in Study 3, where technological facets undergo dynamic shifts, particularly with emerging trends like quantum computers, demanding adaptability in both business and technology approaches.

Additionally, the ease of use of technological solution is linked to the training requirements for Regime's employees to effectively utilize technological solutions. Solutions designed for greater ease of use inherently reduce the training demand, while more complex systems demand a more comprehensive training. In Study 4, the moderate training proved sufficient for correctly understanding the new checklists generated by the AI-based system. These dimensions collectively emphasize the multifaceted nature of skillset and knowledge provision in the transition to Supply Chain 4.0, highlighting its critical role in navigating this transformative environment.

Financial planning and investment strategy

In Study 1, an array of literature has underscored the financially intensive nature of Supply Chain 4.0 (Büyüközkan and Göçer, 2018; Birkel et al., 2019; Krykavskyy et al., 2019; Ghadge et al., 2020). Consequently, another critical factor integral to the transition toward Supply Chain 4.0 emerges: financial planning and investment strategy. This multifaceted aspect of planning encompasses various dimensions, collectively shaping the financial trajectory of this transformative journey. At its core, financial planning demands precise budget allocation, requiring a comprehensive understanding of the financial commitments necessary for technological solution design and adoption, workforce development, business process reengineering, and infrastructure enhancement. Study 4 provides a practical illustration of this dimension, where the modification of the warehouse layout, including the construction of an additional tunnel, offered the potential for reduced travel distances facilitated by the AI-based system. However, such alterations introduce new costs related to con-

struction and potential disruptions in workflow. Additionally, Study 4 highlights the cost implications of acquiring and implementing the AI-based system, encompassing initial setup costs and recurring monthly subscription fees. These elements underscore the need for a thoughtful recalibration of budget allocation by Sienzi.

Furthermore, collaborative planning (see Study 4) between Regime actors and technological solution providers can be fruitful for developing cost-effective Supply Chain 4.0 solutions in supply chains. This approach enables the exploration of ways to create optimal technological systems while minimizing costs, contributing to overall cost management. Additionally, financial planning extends further into the realm of ROI evaluation, necessitating a comprehensive assessment of the tangible benefits derived from the transition. It also encompasses meticulous cost-benefit analysis for identifying both tangible and intangible costs and benefits, enabling informed prioritization of investments and identification of opportunities for cost optimization. Moreover, the concept of Total Cost of Ownership (TCO) gains prominence, advocating a long-term perspective that encompasses ongoing operational expenses, maintenance costs, and potential future upgrades. Furthermore, risk management within the cost domain is imperative, necessitating proactive measures to mitigate financial uncertainties and budgetary variances. Flexibility in cost planning and adaptability to changing cost structures are paramount, acknowledging the dynamic nature of Supply Chain 4.0 technologies and evolving market conditions.

Data privacy and security considerations

The third element pertains to data privacy and security considerations emphasized in the germane literature reviewed in Study 1 (see for example Spanaki et al., 2018; Sobb et al., 2020; Gawankar et al., 2020). The technologies of Supply Chain 4.0, IoP, IoT, CC, BDT, AI, and SI, operate on repositories of data to underpin their transformative impact. Consequently, the imperative of data sharing among supply chain actors emerges as an inevitable reality. In this context, establishing comprehensive security and privacy considerations assumes paramount importance, constituting the bedrock for constructing a robust framework to prevent inadvertent information leakage and unauthorized data access. This multifaceted endeavor necessitates a multifaceted approach. One such approach revolves around security measures. The fortification of security mechanisms stands as a foundational pillar. Robust defenses must be developed to safeguard against potential cyber-attacks that could compromise the integrity and confidentiality of shared data. Conventional security measures are vital to counter prevalent cyber threats and must be procured and implemented collaboratively with cybersecurity experts. However, anticipating potential future threats is equally imperative. As highlighted in Study 3, contemporary security measures may prove insufficient in addressing emerging threats stemming from nascent technologies such as quantum computers. Developing security measures to combat unconventional and futuristic cyber threats necessitates extensive collaboration with academics, governmental bodies, industrial practitioners, and other relevant stake-

holders. This collective effort is imperative for the establishment of a robust broad-scale security infrastructure. The second approach encompasses confidential agreements. The formulation and execution of confidential agreements among actors assume critical significance. These agreements serve as legal safeguards, delineating the rights and responsibilities of each party in the data sharing ecosystem. The third approach incorporates data sharing permissions. Explicit and well-defined permissions for data sharing and usage must be obtained, elucidating the precise purposes for which data may be utilized. This transparency ensures that data is employed judiciously and in alignment with the supply chain's objectives. The last approach refers to regulatory compliance. Compliance with pertinent regulations and laws governing data privacy is an indispensable facet of privacy. Adherence to established standards helps to ensure that privacy matters are approached with due diligence and in full accordance with legal requirements. In Study 4, it is demonstrated that the establishment of a confidential agreement, explicit data sharing permission, and compliance with regulations have effectively addressed privacy matters within the case.

Technological infrastructure development and interoperability

The next critical factor pertains to the development of essential technological infrastructure and interoperability required for the transition to Supply Chain 4.0, in line with the literature reviewed in Study 1 (Luthra and Mangla, 2018; De Vass et al., 2018; Gružauskas et al., 2018; Kamble et al., 2019; Raut et al., 2019). Infrastructure includes high-speed internet connectivity to facilitate data transmission and employing necessary tools essential for adopting advanced technological systems (Luthra and Mangla, 2018; Jabbour et al., 2020; Gupta et al., 2021). High-speed internet connectivity serves as the backbone for exchanging data and information across the supply chain network. Employing necessary tools to serve multifaceted purposes, including but not limited to data storage solutions, building a cybersecurity framework, and developing interoperability standards, to underpin the transformative potential of Supply Chain 4.0. Technological interoperability goes beyond the mere adoption of isolated technologies; it involves ensuring that these technologies seamlessly integrate and communicate with one another. This interoperability extends not only among the various Supply Chain 4.0 technologies being adopted but also with pre-existing technologies like legacy systems. In Study 2, a noteworthy observation was made regarding the positive impact of integrating IoT technologies with ERP systems and facilitating inter-ERP integration among supply chain actors. Achieving these technological integrations necessitates the establishment of interoperable protocols among these diverse technologies. Similarly, in Study 4, clear instances of interoperability were observed, both within the internal technological components of the AI-based system and between the AI-based system and the warehouse's ERP system through API. This underscores the critical role of interoperability in the seamless functioning of Supply Chain 4.0, both within the ecosys-

tem of Supply Chain 4.0 technologies and in collaboration with legacy systems like ERP.

Supply chain collaboration

The last critical factor pertains to supply chain collaboration. In Study 1, several literatures (Szozda, 2017; Frederico et al., 2019; Patrucco et al., 2020; Barata, 2021) underscore this critical factor, which emerges as a linchpin for the successful transition to Supply Chain 4.0 and advanced technological solutions. It is essential for the other critical factors discussed throughout this thesis, such as the reconfiguration of information flow dynamics, data privacy and security, data management, business context understanding, and technological interoperability. A common thread across these critical factors is the imperative of supply chain collaboration. Effective supply chain collaboration can encompass joint planning, coordinated operations, and seamless communication. For example, in Study 4, achieving alignment among Kairos, Sienzi, and Select at strategic, structural, and operational levels was only possible through collaborative efforts. Similarly, Study 3 emphasizes the significance of multi-actor collaboration, involving both business and non-business actors, to develop quantum-resistant BC globally. Moreover, Study 2 sheds light on the benefits of IoT-ERP and inter-ERP integrations, which are only achievable when supply chain actors collaborate harmoniously. Today, collaboration extends beyond internal processes; they are essential for fostering seamless interaction with supply chain partners. Supply chain collaboration enables organizations to adapt swiftly to changing market conditions, customer demands, and emerging technologies. Collaboration can foster innovation by pooling resources, knowledge, and expertise from various partners, which is fruitful for staying competitive in a rapidly evolving landscape. In essence, supply chain collaboration serves as the backbone of Supply Chain 4.0, empowering businesses to fully leverage its potentials and adeptly navigate the complexities of the business realm.

5.2.1 Thesis integrative framework

Based on the synthesis and discussions, the integrative framework for this thesis is presented in Figure 3. This framework outlines the transition to Supply Chain 4.0, involving Regime's supply chains and Niche technological solution providers, and how it entails adapting dynamic capabilities, including sensing, seizing, and transformation. The twelve identified technologies associated with Supply Chain 4.0 illustrate the spectrum of technological resources Niche actors often rely on to develop their corresponding technological solutions. Subsequently, Regime's supply chains embark on the journey toward Supply Chain 4.0 by mobilizing these technological solutions. Consequently, identifying these twelve technologies supports the seizing component of dynamic capabilities.

Furthermore, this seizing is preceded by the sensing component, wherein Regime's supply chains form their judgments regarding the adoption decision. In the

context of this thesis, sensing encompasses the assessment of Supply Chain 4.0 and its subsets to inform these judgments and potentially guide the subsequent seizing. The discerned benefits and challenges associated with the twelve technologies and general Supply Chain 4.0 bolster the sensing component, aiding in forming well-informed judgments.

Ultimately, any sensing and seizing endeavors are accompanied by a transformation phase that necessitates alignment between the solution provider and the Regime's supply chain. The framework outlines critical factors necessary at both the technology and general levels to facilitate this alignment. This alignment is symbiotic, involving a bilateral arrangement between Niche and Regime actors. To address this symbiotic alignment, critical factors at the general level are categorized into three aspects: critical factors for Regime-to-Niche alignment, critical factors for Niche-to-Regime alignment, and critical factors for both Regime and Niche alignment.

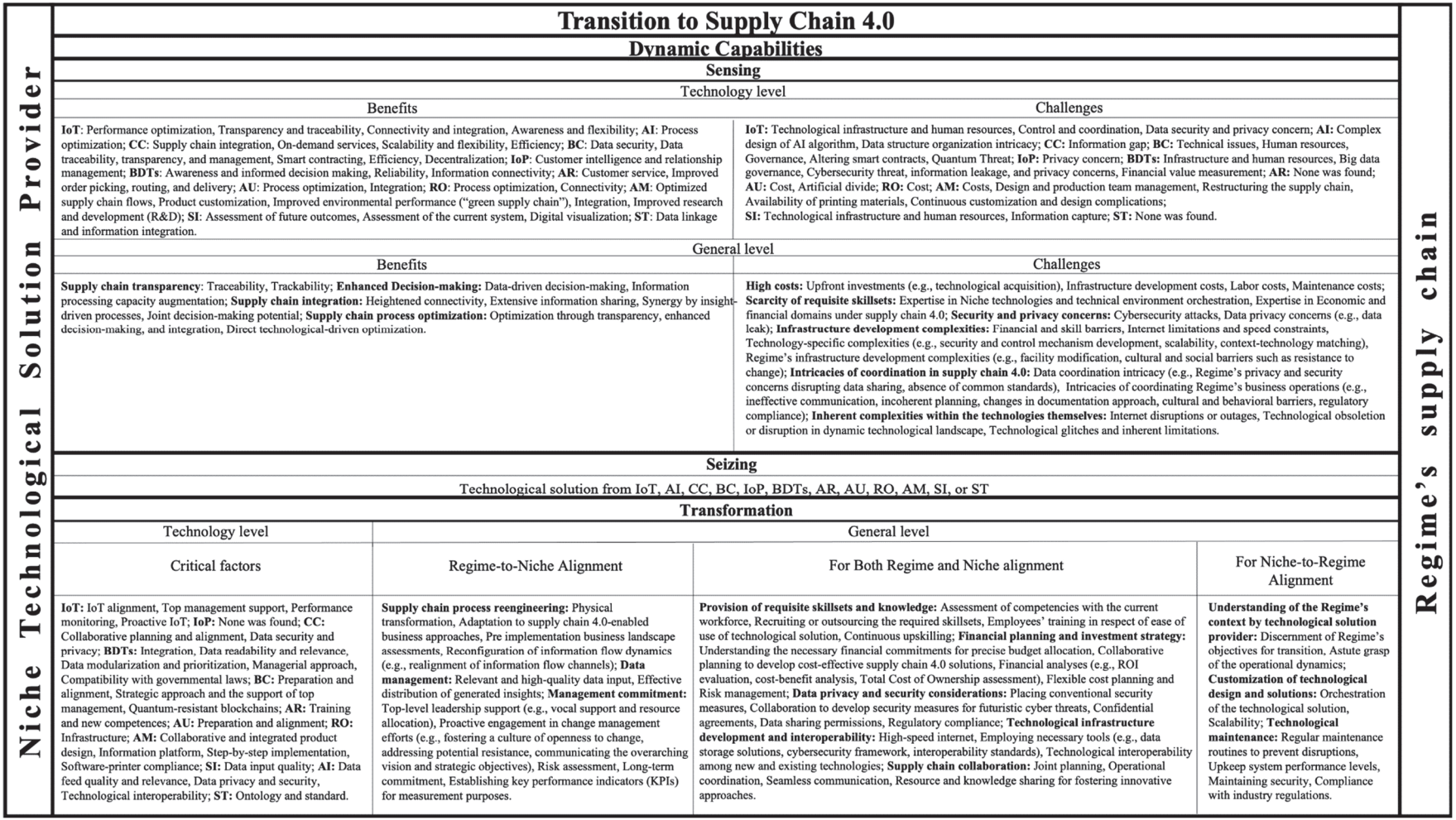

Figure 3: Thesis integrative framework

5.2.2 Supply Chain 4.0 benefits, challenges, and critical factors in the Turkish context

The identified benefits, challenges, and critical factors in this thesis can contribute to the adaptation of dynamic capabilities of Regime actors within Turkey who aim to transition to Supply Chain 4.0. Such transitions within developing economies like Turkey often rely on Niche developments within more robust technology industries in developed economies (Dzyubenko, 2021; Marinas et al., 2021; Monasterio Astobiza et al., 2022), as exemplified by the relationship between Sienzi and Kairos. The targeted contributions of the thesis are in line with Turkey's efforts to accelerate the adoption of advanced technologies across industries (Sahin and Zengin, 2017; Gungor, 2018; Duman and Akdemir, 2021), and with its limited progress in this direction (Atik and Ünlü, 2019; Izmen et al., 2020).

Antony et al. (2023) conducted an online survey involving 149 Industry 4.0 experts and professionals in their cross-sectional and longitudinal study. Their research aimed to explore the benefits, challenges, and critical factors associated with implementing Industry 4.0 in manufacturing processes, specifically focusing on comparing developing and developed economies.

Antony et al. (2023) found that efficiency and agility were paramount to Industry 4.0 adopters in developing economies, as these two benefits were realized comparatively less often in firms within this category than in developed ones. Besides, they identified top challenges prioritized in developing economies, including high costs, a shortage of Industry 4.0 skills, integration of technology platforms, resistance to change, and data security concerns. Furthermore, Antony et al. emphasized the importance of three critical factors, which they deemed equally significant in both developing and developed economies: top management support, employee availability, and alignment of Industry 4.0 solutions to organizational strategies.

The findings from Antony et al.'s (2023) study resonate with the benefits, challenges, and critical factors identified in this thesis, namely supply chain process optimization (benefit); high costs, scarcity of requisite skillsets, intricacies of coordination in Supply Chain 4.0, and security and privacy concerns (challenges); management commitment, understanding of the Regime's context by technological solution provider, customization of technological design and solutions, technological maintenance, provision of requisite skillsets and knowledge, technological infrastructure development and interoperability (critical factors).

Benefits

Given that Turkey is classified as a developing economy (Ersoz et al., 2022; Habeşoğlu et al., 2022), Sienzi's decision to implement the AI-based system for routing optimization in its warehouse, aimed at reducing resource consumption during the picking process, is consistent with Antony et al.'s (2023) emphasis on efficiency as a prioritized benefit in developing economies.

Using the AI-based system, Sienzi has reduced travel distance and time by 27.25% and 22.82%, respectively. Travel time, which constitutes the majority of time consumed in the picking activity, is considered a function of travel distance (de Koster et al., 2007; Tajima et al., 2020). The picking activity accounts for at least 35% of warehouses' total operating cost (Coyle et al., 1996; de Koster et al., 2007; Richards, 2017; Stević et al., 2022). These achievements, together with reduced picking errors and printouts facilitated by using the AI-based system, can significantly contribute to the efficiency of Sienzi's warehousing process, resulting in lower reach truck energy costs for traveling, lower labor costs, lower stationary costs, and lower truck maintenance costs.

Challenges

The challenges encountered in the case study, including costs, structural alignment between technologies, and resistance to change, corroborate three of the five challenges identified by Antony et al. (2023) within the Turkish context. The challenge on skill shortage (Antony et al., 2023) was observed in Select.

While considerable cost savings occurred by using the AI-based system, there are generated costs related to implementation and monthly subscription fees, which could be further escalated by the business adjustment cost if Sienzi were to construct an additional tunnel. Notwithstanding this, adding a tunnel would, in return, increase the additional yield on travel distance by 13.91% as evidenced by the simulation results, which could have counterbalanced the business adjustment cost to a certain extent. Nevertheless, costs associated with such tunnel construction potentially proved to be a hindrance. This is in line with the survey conducted among 108 firms and 110 technology suppliers in Turkey, which reveals that the investment cost is the most evident challenge for the transition to advanced technologies (TÜSİAD, 2017, as cited in Erdil, 2021).

Moreover, the COVID 19 pandemic has brought chaos to many firms. This chaos has also emerged at Sienzi, as highlighted in the collected data, leading to staff experiencing overwhelming stress and fatigue due to the heavy workload extending to the post-pandemic era. Such a situation potentially played a role in the resistance of Sienzi's staff members to major changes and adjustments in their working environment, such as building a tunnel in the warehouse, as part of the Regime alignment with the Niche technological solution. The resistance to change can also be attributed to the fear of losing freedom in performing tasks, as evidenced in Study 4, or the fear of losing the job among low-skilled laborers due to the transition to advanced technologies (Frey and Osborne, 2017; Ghobakhloo and Fathi, 2019).

While reducing job availability for low-skilled laborers, transitioning to advanced technologies creates opportunities for technology-related jobs (Ghobakhloo, 2020). In this regard, Antony et al.'s (2023) challenge related to skill shortages can be attributed to the migration of such highly skilled workers to more developed economies, which offer greater economic stability, higher salaries, and a higher standard of

living. The Organisation for Economic Co-operation and Development (OECD) Secretariat's report underscores that Turkey ranks among the least attractive destinations for skilled workers' migration among OECD member countries (Organisation for Economic Co-operation and Development [OECD Secretariat], 2023), making pertinent employee recruitment within Turkey a complex task and underscoring the importance of training and upskilling, as emphasized in this thesis. The skilled worker shortage challenge in Turkey was also observed in Select, which had struggles with replacing lost software engineers.

This shortage of skilled workers can also condition the other challenge pertaining to structural alignment between technologies (please refer to Study 4). Since the incorporation of advanced technologies into the existing technological architecture of Regime actors can be accompanied by developing new APIs, relevant skillsets, such as programing and software engineering, become significant. Hence, the pool of available skillsets directly links to the possibilities of effective structural alignment between technologies.

Critical factors

Unlike the results of Antony et al. (2023), data security and privacy considerations emerged as critical factors rather than significant challenges in this thesis' case study. The case study demonstrates that using NDA and confidential agreements, in conjunction with compliance with privacy regulations, effectively mitigated privacy concerns. On the landscape level, data protection laws in Turkey could have played a vital role in mitigating privacy challenges in the case study. For example, NDAs and other privacy-related agreements are legally enforceable in Turkey and widely used to protect sensitive information and trade secrets. Turkey's Personal Data Protection Law, known as KVKK (Kanunen Kişisel Verilerin Korunması Kanunu), which was enacted in 2016, primarily focuses on safeguarding individuals' data and regulating companies' data handling practices (Keküllüoğlu and Acar, 2023). Although KVKK has been critiqued for lacking clear accountability standards (Geden and Bensghir, 2019), it is enforced in Turkey and contributes to data protection efforts. While KVKK can be further expanded and improved, comparable approaches can be applied in countries with socio-economic characteristics similar to Turkey. Additionally, the ever-present threat of cyberattacks also necessitates deploying robust cybersecurity measures.

Next, Management can play an important role in overcoming challenges. As highlighted in Study 4, a more comprehensive Sienzi's investigation of the proposed tunnel construction in the warehouse could have identified solutions to minimize space utilization and associated costs. This, in turn, might have yielded a cost-justifiable solution, potentially addressing one of the main reasons for rejecting the tunnel construction. In this regard, management commitment is crucial to initiate such an investigation. Management's role can also be vital for potentially softening the resis-

tance to change arising from heavy workloads during and after the pandemic, apprehensions about losing autonomy in task execution, or fear of job loss. Through various motivating initiatives, managers can help alleviate these concerns and smooth the transition process.

Moreover, governments can be significant for developing necessary education (Rafferty et al., 2019). To bolster the technology-related labor market, the Turkish government, on the landscape level, in cooperation with universities and the private sector, has developed initiatives such as Turkey's digital roadmap, in which training and educating technology-related expertise are emphasized for the transition to advanced technologies (Özlü, 2017; Erdil, 2021). Specifically, Turkey's digital roadmap focuses on the growth and development of six main areas: human, technology, infrastructure, suppliers, users, and governance (Erdil, 2021).

Nevertheless, this roadmap is associated with certain shortcomings. First, it mainly focuses on the transition of the manufacturing industry; second, it lacks complete clarity on possible coordination mechanisms; third, the resources needed for implementing the roadmap are not extensively identified; forth, it doesn't capture the role that can be played by other actors like trade union (Erdil, 2021). Among these shortcomings, an overemphasis on developing a technology-skilled workforce solely for manufacturing neglects the need for similar skills in other areas, negatively impacting the labor market in the long-term. As extensive transition to advanced technologies potentially can engender magnified low-skilled job loss in specific areas, such as logistics and supply chain, beyond manufacturing (Frey and Osborne, 2017), such negligence can lead to a shortage of skilled workers alongside a surplus of low-skilled labor in these areas of the labor market.

Stakeholders at the Regime, Niche, and landscape levels engaged in the transition to Supply Chain 4.0 within Turkey need to adopt a comprehensive approach that encompasses all the critical factors. It is important to develop the necessary infrastructure through collaborative efforts among government, universities, and firms with user-centric approaches. Turkish Niche and Regime actors must consider the symbiotic nature of critical factors necessary for transition alignments. They also need to account for the dynamic feature of the technological landscape, engendering probable needs for reconfiguring established relationships with the advent of disruptive technologies to cope with new challenges and opportunities. In this thesis, the critical factors identified encompass but are not limited to those outlined by Antony et al. (2023). This thesis concurs with Antony et al. (2023) in emphasizing the equal significance of all critical factors.

6. Conclusions

This concluding section offers final remarks that summarize the key aspects of the thesis and answer the research questions. It then elucidates the implications of this thesis for the related literature, theory base, and practice. Finally, the limitations of this thesis are acknowledged, and potential avenues for future research are outlined.

6.1 Concluding remarks

This thesis presents its concluding remarks in light of the findings and discussions. Supply Chain 4.0 signifies the application of advanced technologies into supply chains, ushering in a technological transformation in how supply chains work. The technologies encompassed in Supply Chain 4.0 include, but are not limited to, IoT, CC, BC, AI, IoP, BDTs, AR, AU, RO, AM, SI, and ST, with the first four being the base technologies. Tailoring Supply Chain 4.0 technologies results in varied solutions, and their usability depends on the needs and context of the hosting supply chain. The spectrum of Supply Chain 4.0 technological solutions encompasses full-scale automation to those augmenting and enhancing human-centered operations.

Drawing upon the MLP, Supply Chain 4.0 technological solutions are often developed by Niche actors who leverage advanced technologies from the technological landscape. These Niche developments often occur within developed economies' technology industry due to favorable conditions fostering the growth of firms therein. Regime supply chain actors in developed and developing economies rely on these technology industries' solutions for the transition to Supply Chain 4.0 and its advanced technologies. The solutions are then incorporated into specific Regime's supply chains through technological complementarity and symbiotic alignment encompassing both Niche and Regime actors.

From a strategic management perspective, establishing the Niche-Regime partnership, which is subject to change as the technological landscape evolves, shapes the strategic organization of the supply chain, where interfirm cooperative networks exploit the technological resources of participants to transition to Supply Chain 4.0. To enable such a transition, Regime actors must adapt their dynamic capabilities. Teece's (2019) dynamic capabilities theory, encompassing sensing, seizing, and transformation, underscores the importance of both adoption (sensing and seizing) and alignment (transformation). This implies that transition success is not solely contingent on acquiring Niche solutions but also demands alignment between the Regime's supply chain and the Niche technological solution provider. In this regard, the concept of business-technology alignment underscores the symbiotic nature of this alignment, requiring concerted efforts from both Regime and Niche actors.

This thesis aims to enrich this framework for transitioning to Supply Chain 4.0, through inquiring into the benefits, challenges, and critical factors associated with this transition. Specifically, Research Questions 1 and 2 focus on benefits and challenges to inform judgments about the transition decision, pertaining to the sensing component of Teece's dynamic capabilities. The twelve Supply Chain 4.0 technologies identified in this thesis shed light on the seizing component by elucidating the array of technological resources tailoring into the Niche solutions that Regime's supply chains seek to mobilize. Accordingly, investigating Supply Chain 4.0 technologies' benefits and challenges based upon the identified twelve technologies. Ultimately, Research Question 3 addresses critical factors necessary for alignment, relating to the transformation component.

In response to the research questions posed in this thesis, the following benefits, challenges, and critical factors have been identified. The benefits associated with the transition to Supply Chain 4.0 encompass: supply chain transparency; enhanced decision-making; supply chain integration, and supply chain process optimization. The challenges include: high costs; scarcity of requisite skillsets; security and privacy concerns; infrastructure development complexities; intricacies of coordination in Supply Chain 4.0, and inherent complexities within the technologies themselves. Critical factors were identified within three distinct aspects, in line with the concept of business-technology alignment. Critical factors for Regime-to-Niche alignment involve supply chain process reengineering, data management, and management commitment. Critical factors for Niche-to-Regime alignment include understanding of the Regime's context by the technological solution provider, customization of technological design and solutions, and technological maintenance. Finally, critical factors for both Regime and Niche alignment encompass providing requisite skillsets and knowledge, financial planning and investment strategy, data privacy and security considerations, technological infrastructure development and interoperability, and supply chain collaboration. Furthermore, this thesis underscores the importance of conducting analyses at the technology level, in addition to the general Supply Chain 4.0. To this end, benefits, challenges, and critical factors pertaining to the identified twelve Supply Chain 4.0 technologies are elaborated upon.

6.2 Implications for the pertinent literature and theory base

The present thesis sheds light on a theoretical framework to present an account of the transition to Supply Chain 4.0. This understanding on a theoretical framework is consistent with Weber's (2003) view that – *a theory is an account that is intended to explain or predict some phenomena that we perceive in the world* (p. iv). Accordingly, the thesis' theoretical framework is underpinned by bridging dynamic capabilities, MLP, and business-technology alignment. This framework is then enriched through investigating and identifying benefits, challenges, and critical factors associated with the transition to Supply Chain 4.0.

Essentially, this account suggests that by adapting dynamic capabilities – through sensing, seizing, and transformation – Regime's supply chains can effectively adopt Niche technological solutions related to Supply Chain 4.0, which are hitherto external to them, thereby harnessing their transformative power to enhance competitive advantage. In line with this account, focusing on benefits, challenges, and critical factors can equip the dynamic capability adaptation process with valuable guidance. The MLP provides a structural foundation for identifying the levels involved in adapting dynamic capabilities for the transition to Supply Chain 4.0, while Business-technology alignment extends the transformation component by emphasizing the symbiotic nature of its alignment.

This approach has, to the best of the author's knowledge, not been sufficiently explored in previous Supply Chain 4.0 literature. It is also consistent with the emphasis of this thesis on the diversity of Supply Chain 4.0 solutions, ranging from complete automation to supporting human-centric operations, questioning the over-emphasis on nearly end-to-end automation and integration of supply chain as the sole desired outcome of such a transition, which could lead to significant job loss worldwide. The considerable efficiency and cost savings in Sienzi through a transition to a solution that does not "automate nearly everything" support this view that there is no need to exclusively link Supply Chain 4.0 with rigid end-to-end automation solutions to achieve meaningful benefits. This perspective also addresses the need for balanced human-technology approaches, reflected in ambiguous terms like Supply Chain 5.0. In one of the highly cited articles within the domain, Frederico et al., in 2019, acknowledge the limited conceptualization of Supply Chain 4.0. Then Frederico, in 2021, signals the shift to Supply Chain 5.0. It is incoherent to assume that we can transcend from an under-conceptualized Supply Chain 4.0 to Supply Chain 5.0 within two years. It took no less than half a century from the start of Industry 3.0 to the coinage of Industry 4.0. Accordingly, such a shift from one revolution to the next logically cannot occur within ten to thirteen years, particularly when there is limited conceptualization of the domain. The transition to Supply Chain 4.0 and the adoption of its hitherto external technological resources by Regime's supply chains can be accounted for through the presented theoretical framework and focusing on benefits, challenges, and critical factors can contribute to enriching it.

Moreover, consistent with the view that Supply Chain 4.0 encompasses diversified solutions, driven by its technological composition, this thesis promotes a discourse on the importance of conducting in-depth investigations at the technology level within the Supply Chain 4.0 domain. Given the dynamic and multifaceted nature of the technological landscape, Supply Chain 4.0 technologies are not set in stone. Nevertheless, relevant scholarly efforts could benefit from focusing on Supply Chain 4.0 technologies to advance the frontiers of this domain. Therefore, an implication is to emphasize conducting rigorous research at the technology level.

By developing the insights targeted in this thesis, the research area surrounding Supply Chain 4.0 can progress. This thesis has endeavored to produce insights that can stimulate discussions, further investigations, and refinement within this research field, thereby contributing to the development trajectory of relevant literature.

6.3 Implications for practice

The present thesis offers insights to Regime's supply chains and Niche actors by furnishing them with a comprehensive guide for navigating the transition to Supply Chain 4.0. It sheds light on Supply Chain 4.0 and its technologies, along with associated benefits, challenges, and critical factors important for evaluating and acquiring technological resources, as well as subsequent alignments for maximum utilization in pursuit of the adaptation of dynamic capabilities. While the empirical data and discussions in Study 4 and Section 5.2.2 shed light on various facets of the transition of actors within a developing economy, i.e., Turkey, other studies' literature-driven data and discussions also extend the targeted audience to supply chain actors in developed economies. Adopting actors in both economies often rely on technology industries within developed economies, consistent with the Niche actor of the case study.

A noteworthy implication of this thesis is the importance of symbiotic efforts for alignment in the transformation phase. In essence, Supply Chain 4.0 solution providers and the adopting actors have to commit to concerted efforts to ensure the intended outcome. Besides, they need to pursue changes in the ever-evolving technological landscape to detect and, if needed, harness new opportunities and threats, as evidenced by the example of quantum computers.

Beyond Niche and Regime actors, governments, universities, and other actors in the landscape play an important role in the transition to Supply Chain 4.0. Provision of suitable internet infrastructure, training the required skillsets, developing privacy-related regulations, financial support packages for transitioning firms, research funds, etc., often encompass landscape actors like governments, making them significant in this path. Regime, Niche, and landscape need to collaborate closely to facilitate the transition and to ensure the advanced technologies that underpin Supply Chain 4.0 are sustainably delivering the intended outcome. For example, to deal with a quantum threat to BC and digital signature in general, a collaborative effort is required to ensure widespread quantum-proof cryptography.

6.4 Limitations and avenues for future research

The applied theoretical framework, enriched through focusing on the benefits, challenges, and critical factors, suggests an avenue for future research to consolidate it through further examinations utilizing various empirical approaches. Further research can delve into the identified benefits, challenges, and critical factors at both

the technology and general levels within appropriate empirical contexts to enhance their validity and shed light on the unexplored aspects.

Furthermore, no challenges for AR and ST, and no critical factors for the IoP have been identified in this thesis. This limitation is acknowledged and can provide a sound basis for future research efforts to uncover potential challenges and critical factors for these technologies.

The empirical insights of this thesis stem from a single case study primarily focusing on warehousing process and a specific technological solution based on AI, CC, and SI. Future research can expand these empirical insights by investigating more cases, involving other Niche-Regime scopes of relationships within different supply chain processes, such as transportation or retailing. These studies can focus on alternative technological solutions, including, for example, the IoT, and encompass other geographical locations to potentially reveal new benefits, challenges, and critical factors for the transition to Supply Chain 4.0.

Moreover, this thesis focuses on the Niche-Regime relationship for transitioning to Supply Chain 4.0, assuming that related technological solutions often develop within the boundaries of Niche actors. While it may be challenging to motivate the sharing of knowledge regarding such competitive solutions, future research could investigate cases where leading actors in Regime's supply chains also develop endogenous Supply Chain 4.0 solutions due to their robust research and development, financial, and human resources.

Additionally, this thesis has primarily focused on quantum computers as an example of the potential disruption of established Supply Chain 4.0 technologies by nascent technologies. Future research could delve deeper into alternative scenarios involving other Supply Chain 4.0 and nascent technologies within the ever-evolving technological landscape. Also, future scholarly efforts can explore the empirical implications of quantum computers on BC and digital signatures in general, once this technology has achieved sufficiently mature and widespread status.

Likewise, the interaction between Niche and Regime technologies can extend beyond RFID and ERP. Other legacy systems, such as Electronic Data Interchange and barcodes, can be investigated in a complementary approach with Supply Chain 4.0 technologies.

Ultimately, for future systematic reviews, it is recommended to consider additional databases beyond WoS and BSP while extending the timeframe beyond 2021. This approach will provide a more comprehensive understanding of the subject in question.

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Appendix

Appendix A: Consent Letter Template (Sienzi)

Request for participation in the AI-based warehouse picking research project (AIWP)

Background and purpose
AIWP aims at investigating the order picking optimization in the warehouse.

The general idea is to inquire about an information system for "picking activity" in the warehouse, and to compare the pertinent performance indicators before and after the information system's implementation. Besides, it is targeted to understand what challenges and critical factors are evident in using the system. The system is based on artificial intelligence which has previously shown results in terms of improving productivity and reducing the warehouse picking time and costs.

The AIWP project is headed by Södertörn University, If you have any questions about your data and interview, please contact: Professor Pejvak Oghazi (School of Social Sciences, Sweden, pejvak.oghazi@sh.se).

What does participation in the study entail?
Participation in the study involves sharing performance indicators before and after the system implementation, together with the associated system using challenges and critical factors, and participating in in-depth interviews. The questions will include the operational and logistics performance indicators, and the experience and the overview of implementing the picking system. The research team collects data by measuring the travel time and distance in the pick rounds conducted by the warehouse with and without the system. The data on the warehouse layouts will also

be used for simulating the travel distance with the presence of a hypothetical tunnel.

We will record audio from the interviews.

What happens to the information about you?
The data will be simulated and analyzed in software and applications such as Word, Excel and Stata. The text files containing transcripts from the interview are encrypted and then stored on a secure server. These files are only available to members in the project. The audio files will be stored at a server, which is particularly suitable for securely storing such data.

The results of the AIWP project will be published through scientific manuscripts, available for public. Participants in the study will be given the opportunity to read and approve quotes and information, before publications that are planned with this study. The position and identity of the interviewees, as well as the name of the company(s) can be publicly published.

The AIWP project is scheduled to end by the end of December 2024.

Consent to participate in the study
I, xxxxx xxxxx, xxxxxxx xxxxxxx xxx xxxxxxx of Sienzi Lojistik Antrepo ve Dış Tic. Ltd. Şti, received information about participating in the study (the AIWP project) and hereby I provide my consent for participation. Upon the signature of this consent letter, I, xxxxx xxxxx, xxxxxxx xxxxxxx xxx xxxxxxx of Sienzi Lojistik Antrepo ve Dış Tic. Ltd. Şti, verify that the warehouse party will fully collaborate with the process of data collection for this project.

Company:

Name:

Title:

Date and signature:

Appendix B: Consent Letter Template (Select)

Request for participation in the AI-based warehouse picking research project (AIWP)

Background and purpose
AIWP aims at investigating the order picking optimization in the warehouse.

The general idea is to inquire about an information system for "picking activity" in the warehouse, and to compare the pertinent performance indicators before and after the information system's implementation. Besides, it is targeted to understand what challenges and critical factors are evident in using the system. The system is based on artificial intelligence which has previously shown results in terms of improving productivity and reducing the warehouse picking time and costs.

In the context of AIWP, Select Bilişim Hizmetleri AŞ, the provider of the warehouse's Enterprise Resource Planning, involved in the implementation and usage of this artificial intelligence-based system in the warehouse. Hence, Select Bilişim Hizmetleri AŞ is also to be inquired in the AIWP.

The AIWP project is headed by Södertörn University, If you have any questions about your data and interview, please contact: Professor Pejvak Oghazi (School of Social Sciences, Sweden, pejvak.oghazi@sh.se).

What does participation in the study entail?
Participation in the study involves sharing performance indicators before and after the system implementation, together with the associated system using challenges and critical factors, and participating in in-depth interviews. The questions will include the operational and logistics performance indicators, and the experience and the overview of implementing the picking system. The research team collects data by measuring the travel time and distance in the pick rounds conducted by the warehouse with and without the system. The data on the warehouse layouts will also be used

for simulating the travel distance with the presence of a hypothetical tunnel.
We will record audio from the interviews.

What happens to the information about you?
The data will be simulated and analyzed in software and applications such as Word, Excel and Stata. The text files containing transcripts from the interview are encrypted and then stored on a secure server. These files are only available to members in the project. The audio files will be stored at a server, which is particularly suitable for securely storing such data.

The results of the AIWP project will be published through scientific manuscripts, available for public. Participants in the study will be given the opportunity to read and approve quotes and information, before publications that are planned with this study. The position and identity of the interviewees, as well as the name of the company(s) can be publicly published.

The AIWP project is scheduled to end by the end of December 2024.

Consent to participate in the study
I, xxxxxx xxxxxx, xxx xxxxx xxxxxxxxx xxxxxxx (xxx) of Select Bilişim Hizmetleri AŞ, received information about participating in the study (the AIWP project) and hereby I provide my consent for participation. Upon the signature of this consent letter, I, xxxxxx xxxxxx, xxx xxx of Select Bilişim Hizmetleri AŞ, verify that the Select Bilişim Hizmetleri AŞ party will fully collaborate with the process of data collection for this project.

Company:

Name:

Title:

Date and signature:

Appendix C: Consent Letter Template (Kairos)

Request for participation in the AI-based warehouse picking research project (AIWP)

Background and purpose
AIWP aims at investigating the order picking optimization in the warehouse.

The general idea is to inquire about an information system for "picking activity" in the warehouse, and to compare the pertinent performance indicators before and after the information system's implementation. Besides, it is targeted to understand what challenges and critical factors are evident in using the system. The system is based on artificial intelligence which has previously shown results in terms of improving productivity and reducing the warehouse picking time and costs.

In the context of AIWP, Kairos Logic AB, the provider of the artificial intelligence-based system, involved in the implementation and usage of this system in the warehouse. Hence, Kairos Logic AB is also to be inquired in the AIWP.

The AIWP project is headed by Södertörn University, If you have any questions about your data and interview, please contact: Professor Pejvak Oghazi (School of Social Sciences, Sweden, pejvak.oghazi@sh.se).

What does participation in the study entail?
Participation in the study involves sharing performance indicators before and after the system implementation, together with the associated system using challenges and critical factors, and participating in in-depth interviews. The questions will include the operational and logistics performance indicators, and the experience and the overview of implementing the picking system. The research team collects data by measuring the travel time and distance in the pick rounds conducted by the warehouse with and without the system. The data on the warehouse

layouts will also be used for simulating the travel distance with the presence of a hypothetical tunnel.
We will record audio from the interviews.

What happens to the information about you?
The data will be simulated and analyzed in software and applications such as Word, Excel and Stata. The text files containing transcripts from the interview are encrypted and then stored on a secure server. These files are only available to members in the project. The audio files will be stored at a server, which is particularly suitable for securely storing such data.

The results of the AIWP project will be published through scientific manuscripts, available for public. Participants in the study will be given the opportunity to read and approve quotes and information, before publications that are planned with this study. The position and identity of the interviewees, as well as the name of the company(s) can be publicly published.

The AIWP project is scheduled to end by the end of December 2024.

Consent to participate in the study
I, xxxxxx xxxx, xxx xxxxx xxxxxxxxx xxxxxxx (xxx) xxx xxxxxxx of Kairos Logic AB, received information about participating in the study (the AIWP project) and hereby I provide my consent for participation. Upon the signature of this consent letter, I, xxxxxx xxxx, xxx xxx xxx xxxxxxx of Kairos Logic AB, verify that the Kairos Logic AB party will fully collaborate with the process of data collection for this project.

Company:

Name:

Title:

Date and signature:

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In a world rapidly embracing digitalization, the transition to Supply Chain 4.0 emerges, denoting a technological transformation of supply chains utilizing advanced technologies. This thesis sheds light on this transition by bridging dynamic capabilities, the multi-level perspective, and business-technology alignment, complemented by a multi-method exploration of its benefits, challenges, and critical factors. The multi-method approach integrates data from a transition case in Turkey with insights from the broader literature. The findings provide valuable guidance for practitioners and other stakeholders engaged in transitioning to Supply Chain 4.0. Also, this thesis seeks to contribute to the related literature, opening avenues for further research-based expansions and revisions toward the maturity of this domain. It emphasizes the importance of considering the general concept of Supply Chain 4.0 and its technological underpinnings.

Fakhreddin Fakhrai Rad is particularly interested in the application of technologies in the business realm. His interest domains include Business Processes and Supply Chain Management, International Business, Management Information Systems, Industry 4.0, and Supply Chain 4.0.

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ISBN 978-91-89504-88-2 (print) / 978-91-89504-89-9 (digital) | Södertörns högskola | publications@sh.se

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