Summary of the PhD thesis
Investigating the strategic integration of Industry 4.0 technology and organising for sustainable value creation in traditional manufacturing sectors

PhD Candidate: Claudia Franzè | Course year: 3rd
Academic Tutors: Prof. Emilio Paolucci, Prof. Enrico Macii

1. Introduction – Industry 4.0: from a political initiative to a managerial issue

The term "Industrie 4.0" was first introduced in 2011 in Germany during the Hannover Fair, the world's largest industrial trade fair, by a working group headed by Henning Kagermann, the former CEO of SAP, and representatives from the German government, academia, and industry (Kagermann et al., 2013). The concept of Industry 4.0 (I4.0) emerged as a response to the growing need for increased productivity, efficiency, and competitiveness in manufacturing. It aimed to leverage emerging digital technologies to transform traditional industries and create a new era of smart, connected factories (Ghobakhloo, 2018). The German government initiated the "High-Tech Strategy 2020" in 2012 (now "2030 Vision for Industrie 4.0") to advance I4.0 and secure Germany's global leadership in advanced manufacturing (German Federal Government, 2016; Plattform Industrie 4.0, 2019). This concept not only marked technological progress but also held political significance in enhancing Germany's manufacturing engineering leadership (Kagermann et al., 2013). Since then, I4.0 has become a global movement, with many countries and industries recognising the importance of digital transformation and advanced technology integration in manufacturing. Consequently, various countries have launched their own programs and initiatives to digitise production processes. Similar concepts have emerged worldwide, including "Les Busines du future" (Factories of the Future) in France, "High-Value Manufacturing" in the UK, "Fabricacion Avanzada" (Advanced Manufacturing) in Spain, "Fabbrica Intelligente" (Smart Factory) in Italy, "Manufacturing Renaissance" in the USA, and "Made in China 2025" in China.

Despite significant political and industrial attention, I4.0 should not be viewed as a sudden revolution detached from previous industrial and technological advancements (Liao et al., 2017; Oesterreich & Teuteberg, 2016). Instead, it firmly builds upon the foundations laid by previous industrial revolutions (Culot et al., 2020), and it is further characterised by a high degree of digitalisation, interconnection, automation, virtualisation, and decentralisation across all industries (Bordeleau et al., 2020). Today, I4.0 continues to evolve, driven by advancements in technology, the increasing availability of data, and the need for companies to adapt to a rapidly changing global market (Nayernia et al., 2022). It represents a fundamental shift in the way industries operate, creating disruptions across the system, altering the value creation paths of the companies and sowing profound structural changes (Choi et al., 2022). However, the mere adoption of I4.0 technologies may be a necessary but not sufficient condition to become competitive within emerging paradigms, thus calling for a socio-technical approach to the I4.0 phenomenon, where technological (I4.0 technologies) and social (business/organisational) aspects are seen as complementary and interdependent (Beier et al., 2020; Sony & Naik, 2020). In this vein, organisational theories and other extant models that try to explain how the socio-technical aspects interact by comprehensively considering the "ingredients" or building blocks (BBs) of a successful interplay are hard to find in the literature. Therefore, comprehensive and empirical research in this area is hindered by a partial approach to the topic (Nosalska et al., 2019). To address this gap, the thesis aims at investigating how I4.0 technology and organising can be strategically integrated to create sustainable value through the qualitative analysis of multiple case studies of incumbent companies belonging to different manufacturing sectors.

Accordingly, this dissertation builds on the I4.0 definition of Culot et al. (2020, p.5) as an umbrella concept that does not concern a single radical invention but encompasses various *"'tech ingredients' that are still evolving into new enabling technologies by convergence and mutual*

combination" (Culot et al., 2020, p.5). Subsequently, by adopting a strategic and managerial perspective, the combination of technical innovations and organisational changes are holistically investigated and associated with – among others – significant transformations in business models (Agostini & Nosella, 2021), impacts on the management and organisation of the value chain (Ghobakhloo, 2020; Ramakrishna et al., 2020), effects on crucial contemporary trends such as sustainability (Ghobakhloo et al., 2021) and the need to minimise waste and inefficiencies by embracing a more effective circular economy approach (Teixeira & Tavares-Lehmann, 2023).
This thesis summary is structured as follows. Section 2, by positioning the research within the technology and organising literature, identifies the three building blocks (BBs) contributing to an I4.0 strategic integration – *competencies, business models, and sustainability*. Section 3 outlines the research methodology, offering a roadmap of the study's investigative approach. The results of the qualitative analysis are presented in Section 4 and discussed in Section 5. The thesis summary concludes by summarising the main findings, contributing to theory and practice, addressing limitations, and highlighting research opportunities.

2. State-of-the-art – Industry 4.0 as a socio-technical system

I4.0 is a multi-technology, multi-dimensional, and multi-stakeholder concept aiming to revolutionise manufacturing through digitalisation and explore the convergence of, and the interface and synergies among a bundle of cutting-edge technologies (Teixeira & Tavares-Lehmann, 2023). In the last decade, I4.0 has been studied in various literature streams with different perspectives, where the Engineering/Technology one is dominant and occurs more frequently in the literature, whereas the Business/Economic one represents a relatively more scarce and less explored viewpoint of analysis. Such a perspective differs from the more Engineering/Technology-focused strand as the issues under study are also different, concerning aspects such as business models, value chains, and human resources, among others (Teixeira & Tavares-Lehmann, 2023). In this vein, it is important to note that the research field evolved from a technology-oriented approach to one that significantly emphasises the organisational and managerial aspects, such as the link between digital transformation and value chains, the technologies underlying I4.0 and the impact of their use in business models, the link between I4.0, innovation and sustainability, the relationship between manufacturing industry, technology and SMEs, and the implications of I4.0 for human resources management (Agostini & Nosella, 2021; Ghobakhloo et al., 2021; Teixeira & Tavares-Lehmann, 2023). From this perspective, I4.0 offers novel technologies that, in isolation, are insufficient for sustainable value creation; instead, their strategic implementation is essential to fully leverage their potential (Bittencourt et al., 2021). In fact, recent studies have shown that the mere adoption of I4.0 technologies may be a necessary but not sufficient condition to become competitive within emerging paradigms: to this end, such studies suggested that the I4.0 phenomenon needs to be increasingly framed as a socio-technical system, where technological (I4.0 technologies) and social (business/organisational) aspects are seen as complementary and interdependent (Beier et al., 2020; Sony & Naik, 2020). Framing I4.0 into a socio-technical system means considering the complex interaction between these aspects in pursuing a common goal and the critical interdependence of such aspects that, if not jointly optimised, results in systems with limited effectiveness (Sony & Naik, 2020; van Eijnatten, 2013).
Regardless of the number or novelty of I4.0 technologies, their deployment alone does not lead to revolutionary changes (Nosalska et al., 2019). Introducing new technologies is innovative but not equivalent to full I4.0 implementation, which entails comprehensive business changes enabled by digital technologies and accompanied by holistic company-wide transformations (Ghobakhloo, 2018). Considering Bharadwaj et al.'s perspective (2013) that a digitisation strategy evolves into a "digital business strategy," effective I4.0 implementation requires strategic-level changes (Bharadwaj et al., 2013). In this vein, I4.0 encompasses a wide range of interconnected technical (technologies, systems, solutions) and business (business models, value chains, strategic orientation,

organisational changes) aspects that are interdependent, and their combined effect on companies should be seen as the influence of a complex set of intertwined factors. In essence, I4.0 implementation should be regarded as a "bundle of technical innovations and organisational changes that form a strategic conjunction" (Nosalska et al., 2019, p.856).
However, four issues emerge from the analysis of the literature. First, organisational theories and other extant models that try to explain how the socio-technical aspects interact by comprehensively considering the "ingredients" or building blocks (BBs) of a successful interplay are hard to find in the literature. In this sense, comprehensive and empirical research in this area is hindered by a partial approach to the topic (Nosalska et al., 2019). Second, empirical evidence, especially regarding how a successful strategic interaction between technology and organising occurs in niche and traditional sectors where small and entrepreneurial companies operate, remains limited (Veile et al., 2019). Third, for incumbent companies, the integration of I4.0 into existing systems and business models can be challenging due to various technological, social and managerial factors (Ehrlich et al., 2015; Guerreiro et al., 2018), thus requiring further investigation. Finally, the cost of I4.0 implementation may hinder its adoption, especially when I4.0 triple-bottom-line implications (i.e. economic, environmental and social) are still uncertain due to limited studies in this young research field (Veile et al., 2019). Thus, further research is essential to fully understand the implications and potential benefits of implementing I4.0 for organisations not only from a technological viewpoint but especially from a managerial one. Overall, by adopting a socio-technical system perspective of I4.0, the main gap highlighted in the literature is how the strategic integration – formed by a bundle of technological innovations and business/organisational changes (Nosalska et al., 2019) – occurs especially in incumbent companies aiming at creating long-term economic, social, and environmental value. In this context, the need for strategic-level changes and comprehensive business transformations to fully implement I4.0 implies that investments in technology and organisational changes should align coherently and contemporaneously to achieve the desired outcomes (Bailey et al., 2022). On the basis of all these considerations, the following overarching research question was developed: *How can (I4.0) technology and organising be strategically integrated to create sustainable value?*
To answer this question, a literature review has been conducted in order to identify the main building blocks (BBs) contributing to the successful strategic integration of I4.0 technologies that jointly optimise the socio-technical system. Overall, previous studies that analysed the main trends and state of the art in the literature of I4.0 from the perspective of technology and organising in manufacturing identified the following BBs: *Competencies* (BB1), *Business model* (BB2), *Sustainability* (BB3).

Figure 1 shows the research framework that will guide the dissertation.

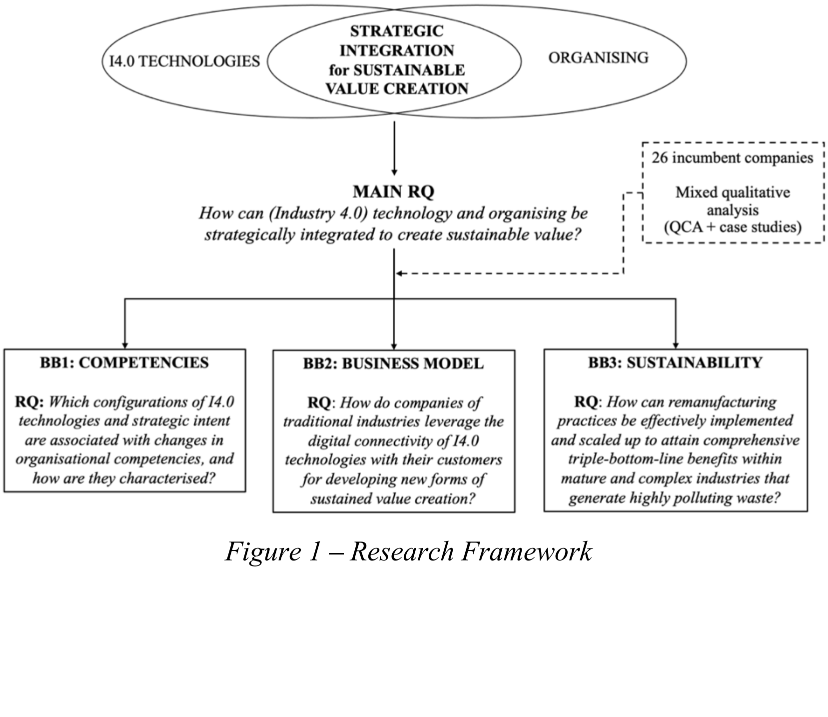

Figure 1 – Research Framework

First, sub-research questions have been developed for each BB based on the conducted literature analysis. Second, the research methodology is illustrated. Finally, results for each BB are presented and discussed in relation to the research framework.

2.1 BB1 – Competencies

The linkage between the adoption of digital technologies, skills, and employment has been the object of an intense and long academic debate, which has gained renewed vigour with the emergence of a new set of interconnected technologies. The breadth of the application of these technologies in production and product development processes entails a high level of complexity in their adoption and integration process (Veile et al., 2021). Studies concur that transitioning to digital technologies and related solutions demands substantial simultaneous changes in a company's organisational and management structure to achieve sustained improvements in efficiency, quality, and productivity, as compared to traditional production assets (Nosalska et al., 2019; Schumacher et al., 2016). Simply implementing I4.0 technologies is insufficient to transform production processes comprehensively. To achieve a successful systemic transformation, companies must also develop new competencies for effectively utilising digital tools and must transform professional practices and organisational culture (Dohale et al., 2023; Fareri et al., 2020).

Therefore, several authors emphasise the need to analyse the organisational changes introduced by I4.0 in terms of the new competencies that should complement its technological adoption (Nosalska et al., 2019; Oesterreich & Teuteberg, 2016; Ortt et al., 2020; Ostmeier & Strobel, 2022; Teixeira & Tavares-Lehmann, 2023). While previous studies acknowledged the importance of linking competencies with new technology adoption (Vakola et al., 2007), companies often struggle to recognise the feasibility of investing in digital technologies and assessing the required skill set in relation to their current range of products and services (Kipper et al., 2021). This challenge is vital for supporting the socio-technical integration necessary for business competitiveness (Ostmeier and Stobel, 2022; Oesterreich and Teuteberg, 2016). In this regard, effective technology adoption for digital transformation not only relies on increased internal technical expertise but also on management's understanding of opportunities and managerial challenges (Shet & Pereira, 2021; Sousa & Rocha, 2019).

However, despite the growing attention on job and skill changes brought about by I4.0, research in this domain is still limited (Moldovan, 2019), and the results from previous I4.0 studies reveal a significant gap between theory and practice concerning the competencies and skills needed for I4.0 (Campion et al., 2020; Shet & Pereira, 2021). While the current state of the art primarily concentrates on building models to evaluate the companies' digital maturity, there is an urgent need to understand the impact that I4.0 technologies have on the workforce (Fareri et al., 2020) in relation to the strategic intent with which these technologies have been adopted.

Thus, several issues remain unexplored. First, clearer boundaries should be established within the broad I4.0 cluster based on the technological characteristics, the strategic intent with which a company invests and uses I4.0 technologies, and the diversity of industrial and competitive contexts in which firms operate. Second, it is still difficult to ascertain whether it is I4.0, as a whole, that requires an upskilling of the workforce or, instead, a subset of technologies within it. Third, it is not clear whether I4.0 technologies require a selective upskilling of only part of the workforce or a more holistic upskilling. Fourth, while some studies suggest that small and medium enterprises may be disadvantaged in their ability to benefit from I4.0 technologies, there is a lack of empirical studies on how firm size plays a role in adopting different I4.0 technologies and the relative upskilling of the workforce. On the basis of all these considerations, the following sub-research question of BB1 has been developed:

RQ.BB1 – *Which configurations of I4.0 technologies and strategic intent are associated with changes in organisational competencies, and how are they characterised?*

2.2 BB2 – Business model

In the context of I4.0 as a socio-technical system, effectively leveraging I4.0 technologies is a critical concern (Bittencourt et al., 2021) because of their profound impact on companies' behaviour and strategies, resulting in significant transformations in product designs, manufacturing processes, operations, and services (Rußmann et al., 2015).

Indeed, I4.0 technologies are disrupting the way in which firms conduct their business (Caputo et al., 2021), opening up new opportunities for value creation, delivery, and capture (Lanzolla et al., 2020), thus enabling business model innovation (Remane et al., 2017; Tahiri, 2022; Teece, 2010), or in case of incumbent companies, business model adaptation (Casadesus-Masanell & Zhu, 2013; Cozzolino & Rothaermel, 2019; Zott et al., 2011). I4.0 technologies are emphasised for their potential to revolutionise two key aspects of the business landscape (Björkdahl & Holmén, 2019; Sahut et al., 2020). Firstly, they can profoundly change the logic behind offering value to customers, and secondly, they can redefine how value creation occurs, not only within the company but increasingly encompassing the interconnected network of relationships that a company possesses (Agostini & Nosella, 2021).

However, despite the significant potential for gain, companies often grapple with a digitalisation paradox: they invest in digital technologies but struggle to achieve the expected outcomes (Ancillai et al., 2023; Gebauer et al., 2021; Kohtamäki et al., 2019; Volberda et al., 2021). Notably, it's not just the technologies themselves but also the distinctive features of interconnectivity and data sharing/management that significantly impact the value creation process (Kraus et al., 2022). However, despite the wide availability of digital technologies, gaps related to a strategic vision of digital connectivity persist, as digital connectivity itself is simply an exchange of data (Shi et al., 2020). For traditional B2B companies, this transition and its value creation potential pose difficulties, requiring broader strategic actions, multiple interventions, and time for a successful transition (Li et al., 2020). While it's crucial for traditional businesses to strategically leverage digital connectivity for holistic digital transformation, it is still unclear how traditional businesses create value from it in a sustained way, being such companies often forced to deal with conflicts and trade-offs between existing (physical) and new (digital) ways of doing business (Verhoef et al., 2021). Moreover, there is a need to refine our understanding of the multifaceted I4.0 phenomenon and explore the practical and theoretical implications of digital connectivity from a value creation perspective(Kraus et al., 2022; Miehé et al., 2022; Verhoef et al., 2021).

Consequently, the focus is on digital connectivity, which is argued to affect the strategic responses of companies to redefine value creation paths (Holopainen et al., 2023), but the logic and the mechanisms that sustain them over time have been less studied (Bresciani et al., 2021; Vial, 2019). An in-depth investigation is necessary to understand how value creation, as driven by digital connectivity, can be sustained in the long term, considering that the manufacturing strategies are closely linked to a traditional supply chain logic and industry structure (Achtenhagen et al., 2013; Remane et al., 2017; Subramaniam et al., 2019).

Thus, it is necessary to gain further insights into the new forms of value creation in B2B relationships driven by an enhanced level of connectivity given by digital technologies and how this value creation is developed in traditional industries. On the basis of all these considerations, the following sub-research question of BB2 has been developed:

RQ.BB2 – *How do companies of traditional industries leverage the digital connectivity of I4.0 technologies with their customers for developing new forms of sustained value creation?*

2.3 BB3 – Sustainability

Since the first industrial revolution in the 18th century, the world has faced the challenge of meeting increasing consumption demands while conserving limited and depleting natural resources and mitigating negative environmental and social impacts (Beier et al., 2020; Müller et al., 2018). In response, I4.0's implications for sustainable development have gained widespread attention, focusing on the triple bottom line framework, sustainable business models, and the circular economy (Khan). Embracing sustainable practices is essential for driving innovative business processes aimed at achieving sustainability through circular economy strategies like narrowing, slowing and closing the resource loop (Geissdoerfer et al., 2017b; Khan et al., 2021). These practices are recognised as vital drivers of competitiveness (Bocken et al., 2014), fostering comprehensive sustainable development (Suárez-Eiroa et al., 2019).

The global trend towards sustainability highlights the challenge of managing pollution and waste generated by mature and complex industries, particularly in developed countries with saturated markets for durable goods (Cardamone et al., 2021). The Circular Economy (CE) emerges as an appropriate solution (Ellen MacArthur Foundation, 2013) for aiming to close the Product Life Cycle (PLC), reduce pollutant emissions, and maximise the utility and value of products (Elia et al., 2017), thereby decoupling economic development from negative environmental consequences (Geissdoerfer et al., 2017a). Among the CE strategies, remanufacturing stands out as an environmentally favourable approach compared to other value recovery options (Goodall et al., 2014). It extends resource use over a product's life cycle by redefining the concept of "end-of-life" (Sundin & Bras, 2005; Vogt Duberg et al., 2020) and preserves not only materials but also the 'embodied energy' from initial manufacturing processes (Goodall et al., 2014; Linder & Williander, 2017). However, two main issues arise.

First, the remanufacturing potential has been hindered by the absence of integrated approaches across various business domains (Jensen et al., 2019; Omwando et al., 2018; Sakao & Sundin, 2019) to catalyse successful remanufacturing efforts, especially in mature and complex industries such as the electrical and electronic equipment (EEE) industry, which generates highly polluting waste known as WEEE (waste of electrical and electronic equipment) which is projected to reach almost 75 million tonnes by 2030 (Forti et al., 2020). Thus, the remanufacturing market remains relatively small, with a remanufacturing ratio of 1 to 50 (Bressanelli et al., 2020; Govindan et al., 2019; Sarkar et al., 2022). This raises questions about whether the potential triple-bottom-line benefits of remanufacturing have been fully grasped (Bressanelli et al., 2021). Finally, both academic and practical literature increasingly call for concrete examples, especially with a sector-specific approach (van Loon et al., 2022).

Second, most circular economy solutions primarily focus on the micro level, which involves individual companies or products, rarely considering the meso level, which encompasses industrial symbiosis and eco-industrial parks, and hardly analysing the macro level, which extends to cities, regions, nations, and international contexts (Ghisellini et al., 2016; Liu et al., 2019; Scarpellini et al., 2019). The effective actions required to promote circular economy solutions depend on a blend of factors across these levels, encompassing technological constraints, market structures, local demands, policy initiatives, regulations, and legislation. Achieving systemic change in high-polluting sectors necessitates strategies for upscaling circular economy models at the macro level. Despite the recognised environmental, economic, and social benefits of remanufacturing, this industry remains relatively small in scale and scope, with limited research attention(Bressanelli et al., 2019; Gallo et al., 2012; Goodall et al., 2014). Additionally, prior studies have emphasised the importance of expanding research on circular business models to adopt an ecosystem perspective that involves multiple stakeholders rather than focusing solely on a company-centric viewpoint (Alblooshi et al., 2022; Kanda et al., 2021; Tapaninaho & Heikkinen, 2022).

To address these challenges in a timely manner, both academic and practical literature increasingly call for concrete examples that embrace a systemic and holistic perspective while exploring interconnected remanufacturing mechanisms needed for triple-bottom-line benefits and their scalability (Bressanelli et al., 2021). On the basis of all these considerations, the following sub-research question of BB3 has been developed:

RQ.BB3 – *How can remanufacturing practices be effectively implemented and scaled up to attain comprehensive triple-bottom-line benefits within mature and complex industries that generate highly polluting waste?*

Following the identification of these BBs with their associated gaps and the development of sub-research questions, mixed qualitative research has been conducted to address the "how" questions.

3. Research methodology: mixed qualitative approach

The qualitative research methodology is an interpretive and naturalistic approach to the study of people, cases, phenomena, social situations and processes in their natural environment (Yilmaz, 2013), whose research process is exploratory and inductive (Ochieng, 2009). Among the various qualitative methodologies, this thesis adopts a *qualitative comparative analysis* (QCA) (Ragin, 1987, 2008) mixed with a *case study approach* (Yin, 2016).

QCA is a configurational, case-oriented methodology that combines case-based research with Boolean algebra and set theory to allow systematic and formalised cross-case comparisons (Ragin, 1987). QCA is suitable for investigating the association between certain configurations of causal conditions and the associated outcomes, as it conceives of cases as configurations of conditions, identifying whether some of these configurations are more consistently associated with an outcome of interest.

Case study methodology is considered appropriate when dealing with situations where there are numerous features of interest and where new phenomena are investigated, posing "how" or "why" questions (Denzin & Lincoln, 2017; Yin, 2016). It enables a careful inquiry to be made and an understanding to be achieved of both the complexity and the nature of the phenomenon under analysis (Voss et al., 2002). Case studies can contribute to theory development and enhancement because they have the benefit of being rich and empirical in describing a particular instance of a phenomenon, placing emphasis on the realistic context in which it occurs, and allowing an inductive approach to be adopted in order to derive implications for theory in a specific field (Eisenhardt, 1998).

3.1 Empirical research setting: traditional manufacturing sectors

The 26 companies considered in this thesis were selected for a large research project (in 2019) funded by the Italian Ministry of Labour and Social Policies. The sample was chosen in a strategic-qualitative manner rather than a quantitative one, and it consists of small and entrepreneurial companies operating in niche and traditional sectors, where the implementation of I4.0 implies that investments in technology and organisational changes should align coherently and contemporaneously to achieve the desired outcomes.

Table 1 – Overview of the companies

Company ID	NACE code	Employees (2022)	Turnover (2022) in M€	Industry 4.0 technologies	Qualitative Mixed Method		Case study	Case study
					QCA	In-depth case study	Multiple case study	Single longitudinal case study
Alpha	24.10 Manufacture of basic iron and steel and of ferro-alloys	1000+	250 - 1000 M€	AI, Sensors, IoT	X	X		
Beta	26.30 Manufacture of communication equipment	51-100	5 - 10 M€	AI, ERP, 3D simulations	X			
Gamma	46.43 Wholesale of electrical household appliances	51-100	10 -25 M€	Data Analysis, RFID, System integration (CRM, ERP)	X	X		X
Delta	20.59 Manufacture of other chemical products n.e.c.	10-50	10 -25 M€	AI, ML, Sensors, System integration (CRM, ERP, MES, WMS)	X			
Epsilon	25.50 Forging, pressing, stamping and roll-forming of metal; powder metallurgy	101-250	25 - 50 M€	Sensors, MES, 3D simulation	X		X	
Zeta	43.21 Electrical installation	10-50	5 - 10 M€	PLM, Additive Manufacturing, 3D simulation	X			

Eta	28.15 Manufacture of bearings, gears, gearing and driving elements	1000+	250 - 1000 M€	AI, ML, Big Data, RFID, IoT, MES, Digital Twin, AR, VR	X		X	
Theta	70.1 Activities of head offices	251-1000	50 - 100 M€	IoT, System integration (ERP, MES, PLM), 3D simulation	X	X	X	
Iota	35.14 Trade of electricity	1000+	> 1000 M€	AI, ML, Big Data, Sensors, IoT, Digital Twin, AR, VR	X			
Kappa	18.12 Other printing	251-1000	50 - 100 M€	ML, IoT, Digital Twin, AR	X			
Kappa2	81.21 General cleaning of buildings	1000+	50 - 100 M€	AI, Cloud platform, System integration (MES, TMS, WMS), Laser scanner 3D Scan to BIM	X			
Lambda	25.72 Manufacture of locks and hinges	101-250	25 - 50 M€	Sensors, System integration (ERP, MES, PLM), 3D simulation			X	
Mu	28.22 Manufacture of lifting and handling equipment	101-250	10 - 25 M€	AI, Cloud platform, IoT, System integration (ERP, MES), AR, 3D simulation	X			
Nu	32.50 Manufacture of medical and dental instruments and supplies	1000	100 - 250 M€	Sensors, IoT, Additive Manufacturing, Digital Twin	X			
Xi	32.50 Manufacture of medical and dental instruments and supplies	51-100	50 - 100 M€	AI, System integration (CRM, ERP, WMS)	X			
Omicron	16.10 Sawmilling and planing of wood	10-50	5 - 10 M€	Data Analytics, Sensors, System integration (ERP, MES)	X			
Pi	10.39 Other processing and preserving of fruit and vegetables	101-250	100 - 250 M€	Data Analytics, Sensors	X			
Rho	28.99 Manufacture of other special-purpose machinery n.e.c.	101-250	25 - 50 M€	Data Analytics, Sensors, VR	X			
Sigma	14.1 Manufacture of wearing apparel, except fur apparel	101-250	25 - 50 M€	PGS, Digital Twin	X	X		
Tau	62.01 Computer programming activities	10-50	< 5 M€	AI, Cloud (SaaS), IoT, System integration	X			
Upsilon	18.12 Other printing	51-100	10 -25 M€	Data Analytics, System integration	X			
Phi	10.85 Manufacture of prepared meals and dishes	251-1000	50 - 100 M€	Sensors, System integration (CRM, ERP, MES)	X			
Chi	30.30 Manufacture of air and spacecraft and related machinery	10-50	<5.000.000	3D simulation	X			
Psi	21.20 Manufacture of pharmaceutical preparations	101-250	25 - 50 M€	AI, ERP	X			
Omega	38.21 Treatment and disposal of non-hazardous waste	51-100	5 - 10 M€	AI, Cloud platform, IoT, System integration (CRM, ERP)	X			
Omega 2	28.22 Manufacture of lifting and handling equipment	251-1000	250 - 1000 M€	RFID, Sensors, IoT System integration (ERP, PDM), Digital Twin, VR	X			

These incumbent companies, belonging to different manufacturing sectors (automotive, textile and apparel, metal and steel, electrical and electronics, among others), traditionally operated with legacy business models, have been immersed in an enforced restructuration process driven by I4.0 and the transition toward sustainable business models (Skellern et al., 2017).

I4.0 significantly impacts companies' competitiveness by facilitating seamless machine interconnection and real-time data sharing both within and between firms while also displacing technologically outdated industrial parks (Munirathinam, 2020). In traditional manufacturing sectors, strategies are closely linked to a supply chain logic, because competitiveness is still based on the delivery of physical goods rather than on digitally mediated transactions, and the prevalence of physical infrastructures (rather than digital platforms) combined with complex supply-chains requires a higher level of investment in new technologies (Bresciani et al., 2021; Caputo et al., 2021). In this context, incumbent companies are often forced to deal with conflicts and trade-offs between traditional (physical) and new (digital) business approaches (Verhoef & Bijmolt, 2019). Indeed, transitioning from traditional industry, where brownfield sites and legacy machines predominate, to I4.0 technologies and practices requires a comprehensive operational overhaul

(Ghobakhloo, 2018). Brownfield sites encompass machines and technologies coming from different vendors that are discontinued or no longer updated and were partially replaced by other technologies (Guerreiro et al., 2018). As such, replacing old plants with a new-generation plant designed for I4.0 is economically and timely inconvenient and technically challenging, thus requiring an upgrade in both the technical and the social components of the system (Beier et al., 2020; Ehrlich et al., 2015).

The shift towards an I4.0 paradigm also encourages the adoption of sustainable business models aligned with social and environmental objectives (Lopes de Sousa Jabbour et al., 2023; Rosa et al., 2020). While industrial activities play a crucial role in the European economy by supplying essential goods and jobs, they exert significant environmental pressure, mainly through emissions, waste generation, and resource consumption (European Environment Agency, 2023). As a response to these challenges, the concept of the circular economy, which envisions a society thriving by reducing waste and repurposing discarded materials for production, has gained global momentum among policymakers, businesses, and academics as a key step towards sustainability (Centobelli et al., 2020). This issue is particularly relevant in mature and complex industries, which produce highly-polluting waste and can benefit significantly from adopting circular practices (Blomsma et al., 2019). For example, the electrical and electronic equipment (EEE) sector, known for generating highly-polluting waste (WEEE - waste of electrical and electronic equipment), could substantially reduce its environmental impact through remanufacturing (Blomsma et al., 2019). According to Forti et al. (2020), the total value of raw materials in WEEE is estimated at approximately 55 billion euros. However, less than 20 per cent of total WEEE is properly collected and recycled worldwide, and implementing circular economy practices in the WEEE industry remains a challenge for companies, organisations, and governments. Consequently, realising the potential environmental, social, and economic benefits of effective remanufacturing practices in the WEEE industry is still in its early stages.

3.2 Cases selection

According to the purpose of each BB, different cases have been selected among the 26 companies in Table 1.

Table 2 – Selection of the cases according to the purpose of each BB.

BB	RQ	Methodology	Cases	Selection principles
1	*Which configurations of I4.0 technologies and strategic intent are associated with changes in organisational competencies and how are they characterised?*	Qualitative Comparative Analysis (QCA)	25 cases	Literal replication logic (Yin, 2016): to cover a sufficiently wide range of sectors and capture the diversity in the effect of technology on the organisational structure and operating model of companies (Patton, 1990).
		In-depth case study	4 cases: *Alpha, Gamma, Theta, Sigma*	Representativeness of the cases to qualitatively investigate the mechanisms and characterisations of the changes in organisational competencies that I4.0 technologies bring about, based on the strategic intent of firms (Marshall, 1996)
2	*How do companies of traditional industries leverage digital connectivity of I4.0 technologies with their customers for developing new forms of sustained value creation?*	Multiple case studies	4 cases: *Epsilon, Eta, Theta, Lambda*	Theoretical sampling: appropriateness of the four cases selected to highlight and extend the relationships and logic among constructs and to ensure external validity (Eisenhardt & Graebner, 2007; Stuart et al., 2002).
3	*How can remanufacturing practices be effectively implemented and scaled-up to attain comprehensive triple-bottom-line benefits within mature and complex industries that generate highly polluting waste?*	Single longitudinal case study	1 case: *Gamma and its Second-life project*	Revelatory case study: not only representative but also with useful variation on the theoretical dimension (Seawright & Gerring, 2008).

4. Main findings

4.1 BB1 Competencies – Which configurations of I4.0 technologies and strategic intent are associated with changes in organisational competencies, and how are they characterised?

The adoption of a mixed method analysis to investigate the sub-research question of BB1 allows to break new ground on (i) the configurations of I4.0 technologies and strategic intent associated with changes in organisational competencies (QCA) and (ii) the nature of the complementarities underlying the configurations and how are changes in organisational competencies characterised (longitudinal case study analysis).

Two QCA have been performed to understand the configurations of high/low skill demand in professional-operational roles (first QCA) and frontline-managerial roles (second QCA). The finding implies that different pathways can lead to high/low skill demand in professional-operational and frontline-managerial roles, but individual paths related to the strategic intent with which investments in I4.0 technologies are pursued are different in terms of empirical importance and effectiveness. The comparison and analysis of the most empirically relevant socio-technical configurations of I4.0 technologies and strategic intent associated with high skill demand in organisational competencies assumed by the 25 Italian companies led to the three main configurations discussed in the following.

Results of the first configuration show how the implementation of virtualisation technologies with the aim of digitalising product development in engineering-to-order manufacturing contexts produces skill changes in professional-operational roles and frontline-managerial roles.

Drawing from the empirical evidence provided by Sigma, it is possible to extend the discussion by generalising the emergence of two key aspects. First, virtualisation technologies applied to product development enable the blending of digital representations of products with their physical counterparts. This implies that product design, prototyping, and testing can occur virtually, bridging the gap between the digital and physical aspects of production. As a result, engineering-to-order manufacturers can create and iterate on designs in a digital space before transitioning to physical manufacturing, thus reducing the need for extensive physical prototyping and testing, leading to cost and time savings. This is possible when product development specialists possess domain/technical knowledge (i.e., the cutting and seam process management, as well as the creation of the dress), as well as new software skills, giving rise to the new role of digital artisans. Furthermore, the more collaborative and interaction-based relationship between product development specialists and the designers of major clients drives greater autonomy in managing customer requirements in product development.

Second, virtualisation technologies facilitate more frequent feedback loops in the production process. This likely refers to the ability to quickly adjust and modify designs based on real-time feedback from customers and stakeholders. The virtual nature of the designs enables quicker iterations and adjustments, promoting a higher level of customisation and responsiveness to customer requirements. Additionally, the development of new customer service models could involve providing customers with virtual simulations or prototypes to gather feedback and make refinements before finalising the design. This is possible when frontline-managerial roles are capable of managing the increased complexity stemming from the multitude of customers, models, garments, sizes, external manufacturers, and suppliers. While the use of new technologies initially led to increased task complexity, it has significantly simplified individual function processes, reduced inaccuracies and rework, and improved overall company operations across diverse functional areas.

On the basis of all these considerations, the following proposition was developed:

Proposition 1: In engineering-to-order manufacturing contexts, the demand for skills is driven by virtualisation technologies, where the operational line blends digital representations of products *with their real and physical counterparts, and the intermediate line manages more frequent feedback loops and the development of new customer service models.*

Findings from the second configuration show how implementing artificial intelligence and data analytics and interoperability and process integration technologies in batch or continuous flow production produces skill changes in professional-operational roles and frontline-managerial roles.

Drawing from the empirical evidence provided by Alpha and Theta, it is possible to extend the discussion by generalising the emergence of two key aspects. First, there is a demand for skills in intermediate and managerial profiles tasked with directing and operating innovation sites related to data analytics and AI. In the context of digital transformation, companies need professionals who can strategize, implement, and manage the integration of data analytics and AI technologies into their production processes. These individuals are responsible for overseeing the use of advanced analytics tools, interpreting data, making informed decisions, and driving innovation within the organisation. They ensure that the collected data is effectively analysed and utilised to optimise processes and enhance productivity.

Second, the demand for skills in professional-operational roles is highlighted in cases where there is a high degree of datafication of production activities and significant investments in AI and data analytics technologies. These roles involve working directly with the technology systems, sensors, and data analytics tools to ensure that data is collected accurately and that insights are extracted effectively. Individuals in these roles are responsible for managing the equipment, setting parameters, troubleshooting issues, and ensuring the smooth operation of the data-driven production processes.

The proposition underscores that the demand for skills varies based on the level of technology integration and datafication. In industries characterised by batch or continuous flow production, where processes are well-established, the demand for skills is particularly pronounced when companies heavily invest in AI and data analytics technologies to optimise their production activities. This investment drives the need for individuals who can effectively manage and operate these technologies.

These companies have experienced shifts in roles and responsibilities, with a greater emphasis on data analysis, automation management, and decision-making. The demand for skills in frontline-managerial roles has increased to oversee the integration of data analytics and AI, while professional-operational roles are crucial for managing the actual implementation of these technologies.

On the basis of all these considerations, the following proposition was developed:

Proposition 2: In batch or continuous flow productions, the demand for skills concerns intermediate/managerial profiles tasked with directing and operating innovation sites in data analytics and AI. The demand for skills in technical/operational roles is high only in cases of high breadth and depth (degree of datafication of production activities) in the level of investments in AI and data analytics technologies for production activities.

Results from the third configuration show how the implementation of artificial intelligence and data analytics technologies with the purpose of digitalising the services in material service sectors produces skill changes in professional-operational roles.

Drawing from the empirical evidence provided by Gamma, it is possible to extend the discussion by generalising the emergence of two key aspects. The operational line, encompassing roles directly involved in data management, data analytics, and logistics, experiences the greatest impact. The need to manage large volumes of data and enhance operational efficiency through analytics results in changes in both the behavioural and functional competencies of these roles. New roles like Data Architects emerge, requiring a blend of IT expertise, domain knowledge, and technical skills specific to product categories. The increased complexity in data management and logistics has led to significant changes in operational line roles. These roles have transitioned to incorporate data-driven decision-making, collaboration, and analytics skills.

Whereas frontline-managerial roles undergo less immediate skill transformation. These roles might not be as directly impacted by the changes brought about by digital technologies until the company develops services that represent substantial innovation in their business models. This suggests that while these roles may not experience immediate changes, they might play a pivotal role when digital transformation leads to the introduction of novel business approaches.

On the basis of all these considerations, the following proposition was developed:

Proposition 3: In material services sectors, the demand for skills is driven by AI and Data Analytics technologies and concerns the operational line and techno-structure (data-related roles). Intermediate/managerial roles are less involved in the skills transformation process until companies develop services that represent a significant innovation in their business models.

4.2 BB2 Business Model – How do companies of traditional industries leverage the digital connectivity of I4.0 technologies with their customers for developing new forms of sustained value creation?

The results of multiple case studies allow to explore how companies of traditional industries leverage digital connectivity with their customers for developing new forms of sustained value creation. Based on the framework of Achtenhagen et al. (2013), the study analyses and reinterprets the strategizing actions and critical capabilities configured by suppliers to achieve and maintain sustained value creation. The findings confirm that in traditional industries, new forms of value creation driven by digital connectivity involve a combination of (i) delivering integrated personalised and innovative product/service solutions, (ii) engaging in value co-creation processes with customers, and (iii) enhancing information transparency and real-time data sharing. More importantly, this study shows that manufacturers are assimilating and scaling up their digital-related capabilities to transform their business models by aligning critical capabilities and strategizing actions for these new forms and combining a change in the governance of transactions with customers to make this value creation sustained, and not only successful – thus leveraging digital connectivity both at the firm and B2B relationship level.

The analysed case studies exhibit similar patterns concerning the role that digital technologies play in creating new ways of connecting suppliers and customers. These encompass the use of virtual simulation and digital twins for real-time prototype development, as well as MES systems designed to connect and integrate all the equipment present on the shop floor and collect, manage, and share any production data. More importantly, the analysis reveals that digitalisation and connectivity in a B2B relationship go beyond merely creating the simple availability of information about production activities. Instead, digital connectivity empowers companies to offer new and more complex products that integrate multiple technologies. While several works have considered the importance of merging new players in the integration of these technologies for value creation or in the creation of new routines that go beyond the traditional supply chain, the results show that these products can still be co-created with the customer, leveraging the well-established relationships while benefitting from the increased transparency and the diffused data sharing, which establish mutual trust and more collaborative governance of the buyer-supplier dyad. The results support the viewpoint of Bresciani et al. (2021) that the strategic leveraging of digital technologies to enhance connectivity in a firm's survival and value creation in the long term is still based on investments in traditional mechanisms of innovation, learning, and interdependence with strategic partners. The resulting new business models entail a value creation that happens over multiple dimensions, and imitation is difficult and costly for competitors. This point is fundamental in light of the previous studies that investigate companies' activities in revising business models thanks to the digital connectivity with network stakeholders for successful value creation while overlooking the importance of this to be sustained.

To this aim, results show that aligning the new forms of value creation enabled by digital connectivity is of critical importance to do it in a sustained way – at the level of the individual firm as well as the B2B relationship. Drawing from the framework of Achtenhagen et al. (2013) on sustained value creation, this study shows that leveraging digital connectivity requires a reinterpretation of the strategizing actions and critical capabilities configured by suppliers. Concerning strategizing actions, digital technologies are shown to allow advanced technologies and production phases to be integrated, but the greater complexity created due to the integration of multiple activities needs to be managed appropriately (*combining specialisation with strategic acquisitions for vertical integration).* The investments in digital technologies made by companies have made it possible to expand their product portfolios by offering more integrated and customised solutions that result in a more complex and complete offer in terms of technologies and competencies (*focusing on a product and customer expansion over different dimensions).* Finally, these companies began to be able to offer customers performances that in the past were considered as "divergent" – such as customised production in small batches at a competitive cost *(combining cost-efficiency with high-quality focus on customised solutions).*

The ability to manage all these transformations contemporaneously is a core aspect that entails rethinking the critical capabilities of companies and properly aligning them toward the new forms of value co-creation identified. The organisational change should not follow the digital connectivity between the supplier and the customer; rather, the alignment between strategizing actions and critical capabilities represents the fundamental "how" this digital connectivity can be exploited for a value co-creation that is sustained. We confirm that the digitally-enabled ways of connecting with customers call for greater data gathering and analysis capacity, with more informed strategic decision-making. Companies aim to align information systems and data with customers to create exactly the value they require, with the integration and connectivity offered by digital technologies to tackle these issues and experiment and share new technical solutions (*configuring a customer-centric value chain)*. We have found that they are instrumental to new forms of product customisation – through data sharing – and more collaborative relationships with the customer, as digital connectivity allows building long-term oriented B2B relationships based on trust and information symmetry. To be sustained long-term, the value creation processes go well beyond the design and production stages. Digital technologies are employed with the aim of having immediate control over the progress of both the design and production processes, controlling all the dimensions of quality and production performances, sharing information in real-time with the customer, determining co-design or co-engineering processes (*integrating buyer-supplier digital resources through digital interfaces).* Digital technologies allow the continuous tracking of products, with the suppliers' end-to-end digital integration with information systems that are key to supporting and fully integrating operational processes (ranging from smart internal logistics to dynamic shipping schedules). The real-time connection of machines directly to these information systems enables companies to precisely monitor and optimise each step of the production and assembly processes through an interpretation of the available data. Thus, the interventions implemented to foster a long-term perspective of digitisation have simultaneously taken place in three directions through (i) data-driven decision-making, (ii) lean management of the most complex organisational structures focused on connectivity with the customers, (iii) long-term enhancement of the employees' connectivity skills and mindsets (*achieving coherence between data-driven decision-making, lean management, and the employees' connectivity skills).*

The engagement of customers in co-creation should also be defined in terms of opportunity and downside sharing for mutual benefit, with the results showing that the strategic renewal enhanced by digital connectivity should further build the concept of dynamic capabilities for digital transformation to make this renewal sustained in the long-term. Thus, a change in the digital-related capabilities – both at the level of the single firm and the B2B relationship – should also complement a change in the governance of transactions with customers, enabling greater transparency and trust in managing the relationship with the customer. Investments in digital technologies that enable collaborative software applications and represent similar connectivity-based solutions for suppliers have been argued to lower asset specificity investments. The analysis highlights the importance of aligning digital investments (on both the supplier and customer side in a B2B relationship) to facilitate the activities required for co-creation and customisation, and with the assets not becoming more specialised as the complexity of the transaction increases. Governance patterns are also impacted by digital technologies in the codification process, as well as by the evolution of the suppliers' competencies over time. The unprecedented access to real-time data should benefit both parties so they can effectively rely on the respective co-creation activities. The higher frequency of transactions mediated by connectivity, coupled with digital trace information about the transacting parties, mitigates the concerns that arise from asymmetric information, lowering the monitoring costs and making the transactions more efficient. Finally, both parties become better at handling uncertainty downsides, as the related costs can be reduced, thanks to better access to (and availability of) information and higher transparency in negotiating and controlling compliance in the fulfilment of the customisation requirements.

The value creation mechanisms that the case study companies created by leveraging digital connectivity are oriented toward accepting and increasing the complexity of products and production processes, with data integrated and shared at every level of activity and thus enriching the established B2B relationships – further integrating the 'physical' and 'digital' ways of doing business. Such mechanisms benefit from a more customer-centric value chain and collaborative and transparent governance of the buyer-supplier relationships. These results differ from and complement previous studies arguing that traditional industries need to leverage larger networks enabled by digital connectivity in order to co-create new rich offerings. Finally, no evidence was found indicating that the size of the companies could (positively or negatively) affect the ability of the companies to establish such new forms of value creation.

4.3 BB3 Sustainability – How can remanufacturing practices be effectively implemented and scaled-up to attain comprehensive triple-bottom-line benefits within mature and complex industries that generate highly polluting waste?

To answer the first part of the third sub-research question concerning the implementation of remanufacturing practices, the strategic innovation lens (Markides, 2008) has been adopted, which is suitable for investigating successful strategies in a context characterised by incremental rather than radical technological innovation. Indeed, without the benefit of a new technological innovation, it is extremely difficult for any company to successfully attack the established industry leaders or to successfully enter a new market. The strategy that seems to improve the probability of success in those situations is the strategy of breaking the rules, whose source of innovation is the redefinition of the business across three dimensions: Who is going to be our customer? What products or services should we offer the chosen customer? How should we offer these products or services cost-efficiently?

Starting from the redefinition of the "who" and "what", the company recombined the customer segments, shifting from B2B to B2C clients and serving people with low incomes or those living in "fragile" conditions and people whose priorities have changed following the sustainability trend and environmental concerns. The company became customer-oriented rather than supply-oriented as it transitioned from spare parts distribution to white goods remanufacturing. This resulted in establishing a laboratory and a (reverse) supply chain to support the handling of products (from discarded to remanufactured). Overall, the company moved from offering products to offering solutions that fulfil customer needs: indeed, along with remanufactured white goods, a 12-month warranty and technical assistance service are provided.

The "how" dimension has been analysed using three theoretical perspectives (operational, technological, strategic) for implementing successful remanufacturing practices.

The operational perspective concerns resequencing business processes. Second-life required a reorganisation of business process operations: the selection of end-of-life white goods needs in-

depth experience and technical knowledge to choose those goods whose components can be easily and cheaply replaced so as not to incur too costly remanufacturing processes. This task requires detailed knowledge of the product life cycle, as well as to perform remanufacturing in 4-5 hours. Indeed, people are specialised for each stage of the remanufacturing process (selection, collection, remanufacturing, sale, after-sales service). Overall, Gamma optimises the order of remanufacturing processes to break the path dependency of the traditional linear make-use-dispose model while maintaining the logic of specialisation linked to best practices gained in household appliance spare parts and repairs.
The technological perspective concerns blending physical and digital realms. Gamma digitalised its physical infrastructure to manage the complexity of the information and the number of spare parts that had to be processed and needed for the remanufacturing process. It also introduced an increasing number of resources with Data Management and Data Analytics skills into the company. The many years of experience in the repair and spare part industry led Gamma to develop an internal platform that seamlessly blends the physical and digital realms. This platform facilitates integrated management of technical documentation, images, and product information, containing more than 2 million data entries. It is fed by master data and integrated with the warehouse management software.
Finally, the strategic perspective concerns transferring risks in the supply chain by centralising market analysis and forecasting activities and decentralising the remanufacturing activities. Gamma's business model of the "pure sales" of spare parts evolved into a circular business model based on remanufacturing. From a CE perspective, this can be seen as a way of shifting the risks of the traditional linear supply chain model from the consumer to the supplier and of embracing an ecosystemic logic in which interdependencies are no longer linear but circular and organic.
The joint and synergistic implementation of these mechanisms has led to the achievement of the following triple-bottom-line benefits. From an environmental perspective, the product lifecycle is extended by 5-7 years. During 2022, the reconditioning of 3.600 washing machines allowed 240 tonnes of material resources to be saved. From an economic perspective, the company generates 300/month of white goods, which account for 75.000€/month revenues (1M€/year), while the customer can buy remanufactured white goods at a price that is at least 50% lower than the price of a new device. From a social perspective, the Second-life project trains and employs individuals with social or economic problems in collaboration with the missionary service of young people (SERMIG).

To answer the second part of the third sub-research question concerning the scalability of a remanufacturing model, the business model of Gamma-Second-life is harnessed to build a framework for large-scale remanufacturing. A broader territorial coverage would diffuse the socio-economic and environmental benefits of the remanufacturing process beyond urban areas. Additionally, leveraging cost savings from scale and scope economies would increase the financial sustainability of increasingly more complex remanufacturing.
Such a model shows that a large-scale remanufacturing system can rely on the synergy between a central hub handling all management activities – supply chain logistics, data integration, analysis and sharing, market analysis, forecasting - and decentralised units handling all remanufacturing operations – e-waste collection, remanufacturing, repairs and final sales of appliances. The central hub needs to be an efficient large-scale spare parts dealer since the supply chain of appliances' components is inherently complex due to the variety of spare parts with different obsolescence and intermittent demand patterns that complicate any stock control strategies and forecasting.
The findings show that the transition to an integrated, systemic circular economy model can be grounded in the upscaling of a sustainable business model. The actual modalities of interaction between the hub and its spokes can be tailored to the specific business ecosystem of a territory. For example, the central hub could manage the franchising of remanufacturing labs or be a partner in a cooperative of small independent remanufacturers. The individual repairers affiliated with the system could be employees of remanufacturing labs or autonomous workers. However, beyond the

specific contractual agreements between parties, some core features characterise the model independently of the location of the application. Thus, the following propositions pinpointing the main elements of this system have been developed.

On the one hand, it is underlined the importance of distinguishing data that can be standardised, collected in the central hub, and used to generate predictive knowledge from the technical know-how embedded in the human capital of experienced technicians that is best transferred through one-on-one interactions:

P1. A large-scale remanufacturing system should organise knowledge, data, and information flows according to their transferability across individuals and platforms. Tacit repair expertise and know-how should be diffused in small centres spread around the territory; conversely, big data analytics about parts and markets should be centralised and shared within the supply chain to leverage scale economies in data management.

On the other hand, the key elements for managing the physical flow of goods and the location of physical infrastructures are highlighted:

P2. A large-scale remanufacturing system should organise flows of physical goods according to their weight and bulkiness. Minimising the transport of large appliances requires that remanufacturing labs are close to waste collection centres and potential customers. Conversely, spare parts and components can travel long distances, thus the central hub can be located wherever suitable to have its physical infrastructure.

Finally, the geographic logic behind the model is emphasised: the three levels proposed in the model capitalise on the centralisation of high-tech tasks in the hub while moving to more remote areas with increasingly low-tech solutions:

P3. A large-scale remanufacturing system shaped as a star network enables the integration and synergy between centralised high-tech solutions in a core company (hub) with decentralised remanufacturing labs and repairs (spokes), spreading triple-bottom-line benefits on the local ecosystem.

The analysis is rooted in the business case under examination and its regional context, therefore its extrapolation to other markets or areas should be done carefully. For example, in the context of multiple mega-cities, it might be necessary/possible to have multiple hubs and a different network structure to cover the entire territory. Nonetheless, the managerial implications deriving from this investigation can inform a broad spectrum of actors involved in the development of CE ecosystems.

5. Discussion

Drawing from the socio-technical system theory to frame the complex phenomenon of I4.0, the dissertation aims at investigating how technology and organising can be strategically integrated to create sustainable value.

The research framework that guided the study is based on the following premises. I4.0 is not just a technological phenomenon but also a human and social reality, characterised by the intricate interplay between technology, organisational changes, and socio-economic factors (Teixeira & Tavares-Lehmann, 2023). As such, implementing I4.0 technologies in a complex socio-technical system involves addressing not only technical challenges but also organisational, management, and social concerns (Nosalska et al., 2019). This reflects the need for a holistic approach to understanding how Industry 4.0 technologies interact with various organisational dimensions, ultimately shaping the way companies function and innovate, acknowledging that I4.0 is not solely a technological shift but a complex sociotechnical transformation (Beier et al., 2020). Finally, the success of Industry 4.0 relies on how well these elements collaborate and complement each other to drive innovation, efficiency, and sustainability in modern manufacturing and beyond (Dohale et al., 2023).

Thus, to answer the overarching research question (*How can (I4.0) technology and organising be strategically integrated to create sustainable value?*), a literature analysis has been first conducted that identified three main building blocks (*competencies, business model, sustainability*) that contribute to the strategic integration of I4.0 technological and organisational aspects. Subsequently, the role of each BB in the relationship between technology and organising has been analysed and discussed through a mixed qualitative approach by conducting a qualitative comparative analysis and case studies. The results of this investigation are discussed in the following.

BB1 competencies highlights that successful implementation of I4.0 requires not only the adoption of new technologies but also the development of new competencies among employees. It emphasises the need for upskilling and reskilling human resources to effectively utilise I4.0 tools and to adapt to changing professional practices and organisational culture. The integration of technical domain expertise and managerial understanding is crucial for successful transformation. This resonates with the idea of Industry 4.0 as a sociotechnical system where technology and workforce competencies are intertwined (Ostmeier & Strobel, 2022). In line with prior research on technology and organising, this dissertation points to the increasingly complex entwining between people and the technologies on which they rely. Viewing technologies as entities that are autonomous objects that are only tied to the social environment via use relations is no longer productive. Today, emerging technologies accentuate this point as they generate myriad new types of possible relations between people, technology, and organising. Now, technologies are increasingly enacted—they come into being and have meaning in the world—through these relations (Bailey et al., 2022).
In this relation, technology replaces humans only in automation tasks, while it complements them in cognitive tasks (Veile et al., 2021). Finally, current emerging technologies—although still in their infancy—are becoming increasingly autonomous and intelligent and, thus, carry the possibility of supplementing or replacing human cognition and action. Such technologies continuously acquire knowledge and skills, possibly operating autonomously or in concert with humans. This ability to learn and act autonomously makes emerging technologies very different from most technologies historically used in organisations (Bailey et al., 2022).

BB2 business model explores how Industry 4.0 technologies transform the traditional way companies conduct their business and open up new opportunities for value creation through the leverage of their digital connectivity for interoperable and collaborative data sharing. It emphasises that companies need to strategically utilise I4.0 technologies to adapt or innovate their business models to remain competitive, driving changes in product designs, manufacturing processes, operations, and services, ultimately reshaping how companies operate in the market.
I4.0 technologies enable new approaches to innovation and collaboration within and across organisations. As people and organisations engage in new forms of collaboration, they accelerate the recombination of ideas and the development of novel products and processes (Lanzolla et al., 2023). They also rapidly disrupt existing market and industry structures. Moreover, organisational boundaries become increasingly porous: in many cases, the ideas and knowledge that prove most relevant for innovation reside without, not within, a focal organisation (Bailey et al., 2022).

BB3 sustainability discusses how Industry 4.0 technologies can contribute to sustainable practices, such as circular economy and remanufacturing in waste-intensive sectors. It suggests that remanufacturing implementation requires a comprehensive approach that includes operational, technological, and strategic considerations. It addresses challenges in implementing sustainable practices and scaling them in mature industries to achieve circular economy goals. This aligns with the idea that Industry 4.0 technologies can be harnessed to address environmental and social challenges through novel approaches (Ching et al., 2022).
The effective implementation of remanufacturing practices for achieving triple-bottom-line benefits is seen through the strategic innovation lens aiming at asking three fundamental questions

(who/what/how). By breaking the rules of the game and thinking of new ways to compete, a company can strategically redefine its business and catch its bigger competitors off-guard (Markides, 2008).
In particular, the results break new ground in effective remanufacturing practices, unveiling three pivotal mechanisms which, when synergistically employed, allow white goods remanufacturing to be successfully undertaken and holistic triple-bottom-line benefits to be achieved. The study also highlights that the successful implementation of remanufacturing practices does not demand a radical transformation of the strategic assumptions underlying a business model.
It also shows that, although data management competencies are not new, Gamma, through the Second-life project, was one of the first companies to bring them together in the configuration needed to square the circle between market responsiveness and demand uncertainty in the WEEE sector. Consequently, to remain proactive and avoid being caught off-guard, managers should increasingly scrutinise the evolving technological landscape and strategically harness data to innovate their organisational operations for the broader societal good (Bressanelli et al., 2021). Finally, the study contributes to the remanufacturing literature by illustrating how these mechanisms not only result in successful remanufacturing implementation but also emphasise effective management of uncertainties through the enhancement of core competencies and the cultivation of circular and organic interdependencies for broader scalability of the model.

Overall, from the discussion of the findings, some general considerations emerge.

First, the evidence underscores the multifaceted nature of I4.0 as a sociotechnical system, where technology, organisational changes, human resources, and sustainable practices are interconnected. In this vein, a strategic approach is vital to understanding how I4.0 technologies interact with various organisational dimensions, acknowledging that I4.0 is not solely a technological shift but a complex socio-technical transformation involving changes that go beyond technology and impact the entire organisation (Beier et al., 2020). As such, I4.0 technologies should first align with an organisation's strategic goals and objectives, otherwise, investments in technology may not yield the desired outcomes (Nosalska et al., 2019). Accordingly, in the dissertation, three main aspects of strategic integration between technology and organising have been analysed, highlighting the interdisciplinary nature of their contribution that, given its complexity, it requires strategic guidance toward sustained value creation and the right prioritisation of investments based on their potential impact on the company's competitiveness and long-term viability (Choi et al., 2022). Thus, efficient and effective resource allocation requires well-informed strategic decisions about where and how to invest resources to optimise outcomes and create value (Bharadwaj et al., 2013). All of this must take into account the dynamism of the context, as I4.0 is an ongoing process of innovation and adaptation, where continuous monitoring, evaluation, and adjustment of the technology implementation strategy is fundamental to stay aligned with evolving market conditions and emerging technologies (Nayernia et al., 2022).

Second, the evidence shows an increasingly complex entwining between people and technologies: I4.0 technologies are not autonomous objects tied to the social part of the system via use relations but generate myriad new possible relations between people, technology, and organising enabled by new I4.0 competencies (Veile et al., 2021). I4.0 technologies do not operate in isolation. Instead, their effectiveness and impact depend on their interaction with various non-technological aspects of the organisation and its environment. This includes factors such as human competencies, organisational culture, and strategic planning. In other words, technologies cannot function optimally unless they are integrated and aligned with these non-technological elements (Teixeira & Tavares-Lehmann, 2023). The growing complexity of the relationship between humans and I4.0 technologies highlights how these technologies are not mere tools but rather catalysts for new ways of organising and operating, emphasising the importance of considering both technological and non-technological factors when implementing and utilising I4.0 technologies effectively within an organisation. Thus, today's technologies emerge through a set of expanded relations and continue to emerge in new ways as those relations evolve (Bailey et al., 2022).

Third, a relational perspective between technology and organising emerges. The success of I4.0 relies on how effectively these elements collaborate and complement each other to drive innovation, efficiency, and sustainability in modern manufacturing – as described by Bailey et al. (2022) as "complex constellations of relations". Indeed, unlike previous industrial revolutions, I4.0 technologies do far more than automate and informate, posing new and significant challenges to organisation science that set them apart from prior technologies. The analysed cases demonstrate that I4.0 technologies are not mere objects around which organisational processes and phenomena occur. Instead, they possess a relational nature (Bailey et al., 2022), fundamentally intertwining and interacting with organisational processes and phenomena. In fact, even scholars with a focus on technology within the organisational context now acknowledge that the material and social aspects of technology are intricately woven or entangled within a complex network of mutually constitutive relationships, and when integrated together, they can enable modern organisations (Bordeleau et al., 2020).
Accordingly, I4.0 technologies might affect many parts of the organisation simultaneously, enabling new interdependencies within and between units and with actors that many organisations have typically considered to be outside their boundaries (Veile et al., 2019). Such pervasiveness of technology is increasingly infusing everything that happens within and around organisations, as shown by the case studies analysed, requiring a comprehensive understanding of key ingredients for a successful I4.0 strategic integration. This relational perspective well reflects the dynamic vision of Industry 4.0 technologies: rather than viewing technologies as fixed entities in fixed relations, it is more fruitful to approach them as made up of relations and entwined in relations that are constantly evolving (Bailey et al., 2022).

An evolution that becomes valuable for initiating the interpretation of the results of the case studies from a more advanced Industry 4.0 perspective, which could lay the groundwork for future research. In fact, the evidence from the cases highlights those initial aspects characterising Industry 5.0 and reflecting the ongoing historical transition period from Industry 4.0 to Industry 5.0. Companies are evolving from mere technological adoption to a systemic socio-technical transition that lays the foundations for Industry 5.0, whose pillars of human centricity, resilience, and sustainability (Enang et al., 2023; Ghobakhloo et al., 2023) have already begun to emerge from the analysed cases.

6. Conclusions

The thesis aims at investigating how Industry 4.0 technology and organising can be strategically integrated into incumbent companies to create sustainable value. This purpose aligns with the evolution of the related academic literature from a technology-oriented approach to one that significantly emphasises the organisational and managerial aspects.
Two main contributions to theory emerge from the thesis. First, the adoption of a strategic and managerial perspective allows to holistically investigate how the combination of technological innovations and organisational changes drives sustainable value creation in incumbent companies. As this perspective represents a relatively more scarce and less explored viewpoint of analysis, it requires particular attention to frame I4.0 not just as a technological shift but as a complex socio-technical transformation. In this vein, three social aspects are comprehensively explored (*competencies, business model, sustainability*) not only from a theoretical viewpoint but also from a practical one with the analysis of real case studies, thus overcoming the common partial approach to the topic. The interplay of these aspects with I4.0 technologies allows to draw conclusions regarding the strategic integration of technology and organising for sustainable value creation. Although the results of each BB are relevant in themselves, it is the overall view that contributes to the advancement of knowledge in this literature. Second, the thesis addressed the technological,

social and managerial challenges that incumbent companies have to face when integrating I4.0 technologies into their existing systems and business models, therefore highlighting how every technological change/revolution is not a sudden and isolated event but requires real integration into existing business models. The results show how the change that has occurred in each BB is based on pre-existing/legacy competencies, business models, and sustainability aspects that are already inherent in the company, which are complemented and evolve with the strategic integration of I4.0 technologies. These considerations are relevant and specific to research settings where supply chain competitiveness is still based on the delivery of physical goods rather than on digitally-mediated transactions, thus contributing to a less explored area compared to digital native companies.

From a practical viewpoint, by providing empirical evidence based on real case studies, the thesis aims to bridge the gap between I4.0 technology investments and the creation of sustainable value, also reconciling the diverging views of management and technical experts. This contribution involves developing more sophisticated and integrated models for interaction between managers and engineers, fostering successful internal corporate communication, and promoting the sharing of best practices. The ultimate goal is to enhance the added value, growth, and competitiveness of companies. In this vein, the thesis also contributes to the creation of more specific I4.0 adoption models that could help a broader number of companies to successfully invest in such direction, understand the mechanisms for creating value, compare alternative strategies, evaluate expected economic returns, and establish the degree of complementarity with other practices. Finally, the thesis contributes to understanding the implications and potential triple-bottom-line benefits of implementing I4.0 for organisations not only from a technological viewpoint but especially from a managerial one.

The novel aspects of the thesis are primarily twofold. First, the analysis is structured to address the integration challenge of literature streams. It examines competencies, business models, and sustainability from a strategic perspective that serves the integration of technology and organising for sustainable value creation. In this way, these streams are not analysed in isolation but within a strategic and managerial context, highlighting their relational aspect intertwined with other elements of the I4.0 socio-technical system. Secondly, the theoretical relevance of these literature streams is supported by empirical evidence, making the BBs robust and thus laying solid foundations for future research. The empirical analysis shows that I4.0, to lead to the creation of sustainable value, requires changes in competencies and roles, business models, and sustainability practices, and these aspects cannot be separated from each other.

Despite the empirical relevance of the thesis, it is important to acknowledge its limitations related to the adopted methodological approach. Although the qualitative approach with which the analysis has been conducted allowed a deep understanding of the phenomenon under investigation to be attained, the specificities of the context limit the external validity and generalisability of the results obtained in diverse contexts. Future research could consider other manufacturing companies not included and represented in this thesis (e.g., advanced manufacturing, furniture and wood production, construction, mining, and extractive companies), as well as foreign companies operating in developed and developing countries. Future research could also investigate, from a longitudinal perspective, the causality between the proposed managerial aspects, the implementation of I4.0, and the creation of sustainable value.
Additionally, large-scale quantitative studies could be instrumental in confirming the generalisability of the findings and testing the developed propositions.

Bibliography

Achtenhagen, L., Melin, L., & Naldi, L. (2013). Dynamics of business models - strategizing, critical capabilities and activities for sustained value creation. *Long Range Planning*, *46*(6), 427–442.

Agostini, L., & Nosella, A. (2021). Industry 4.0 and business models: a bibliometric literature review. *Business Process Management Journal*, *27*(5), 1633–1655.

Alblooshi, B. G. K. M., Ahmad, S. Z., Hussain, M., & Singh, S. K. (2022). Sustainable management of electronic waste: Empirical evidences from a stakeholders' perspective. *Business Strategy and the Environment*, *31*(4), 1856–1874.

Ancillai, C., Sabatini, A., Gatti, M., & Perna, A. (2023). Digital technology and business model innovation: A systematic literature review and future research agenda. *Technological Forecasting and Social Change*, *188*, 122307.

Bailey, D. E., Faraj, S., Hinds, P. J., Leonardi, P. M., & von Krogh, G. (2022). We Are All Theorists of Technology Now: A Relational Perspective on Emerging Technology and Organizing. *Organization Science*, *33*(1), 1–18.

Beier, G., Ullrich, A., Niehoff, S., Reißig, M., & Habich, M. (2020). Industry 4.0: How it is defined from a sociotechnical perspective and how much sustainability it includes – A literature review. *Journal of Cleaner Production*, *259*, 120856.

Bharadwaj, A., El Sawy, O. A., Pavlou, P., & Venkatraman, N. (2013). Digital business strategy: toward a next generation of insights. *MIS Quarterly*, *37*(2), 471–482.

Bittencourt, V. L., Alves, A. C., & Leão, C. P. (2021). Industry 4.0 triggered by Lean Thinking: insights from a systematic literature review. *International Journal of Production Research*, *59*(5), 1496–1510.

Björkdahl, J., & Holmén, M. (2019). Exploiting the control revolution by means of digitalization: value creation, value capture, and downstream movements. *Industrial and Corporate Change*, *28*(3), 423–436.

Blomsma, F., Pieroni, M., Kravchenko, M., Pigosso, D. C. A., Hildenbrand, J., Kristinsdottir, A. R., Kristoffersen, E., Shahbazi, S., Nielsen, K. D., Jönbrink, A.-K., Li, J., Wiik, C., & McAloone, T. C. (2019). Developing a circular strategies framework for manufacturing companies to support circular economy-oriented innovation. *Journal of Cleaner Production*, *241*, 118271.

Bocken, N. M. P., Short, S. W., Rana, P., & Evans, S. (2014). A literature and practice review to develop sustainable business model archetypes. *Journal of Cleaner Production*, *65*, 42–56.

Bordeleau, F.-E., Mosconi, E., & de Santa-Eulalia, L. A. (2020). Business intelligence and analytics value creation in Industry 4.0: a multiple case study in manufacturing medium enterprises. *Production Planning & Control*, *31*(2–3), 173–185.

Bresciani, S., Huarng, K. H., Malhotra, A., & Ferraris, A. (2021). Digital transformation as a springboard for product, process and business model innovation. *Journal of Business Research*, *128*(February), 204–210.

Bressanelli, G., Perona, M., & Saccani, N. (2019). Challenges in supply chain redesign for the Circular Economy: a literature review and a multiple case study. *International Journal of Production Research*, *57*(23), 7395–7422.

Bressanelli, G., Pigosso, D. C. A., Saccani, N., & Perona, M. (2021). Enablers, levers and benefits of Circular Economy in the Electrical and Electronic Equipment supply chain: a literature review. *Journal of Cleaner Production*, *298*, 126819.

Bressanelli, G., Saccani, N., Perona, M., & Baccanelli, I. (2020). Towards Circular Economy in the Household Appliance Industry: An Overview of Cases. *Resources*, *9*(11), 128.

Campion, M. C., Schepker, D. J., Campion, M. A., & Sanchez, J. I. (2020). Competency modeling:

A theoretical and empirical examination of the strategy dissemination process. *Human Resource Management*, *59*(3), 291–306.

Caputo, A., Pizzi, S., Pellegrini, M. M., & Dabić, M. (2021). Digitalization and business models: Where are we going? A science map of the field. *Journal of Business Research*, *123*(October 2020), 489–501.

Cardamone, G. F., Ardolino, F., & Arena, U. (2021). About the environmental sustainability of the European management of WEEE plastics. *Waste Management*, *126*, 119–132.

Casadesus-Masanell, R., & Zhu, F. (2013). Business model innovation and competitive imitation: The case of sponsor-based business models. *Strategic Management Journal*, *34*(4), 464–482.

Centobelli, P., Cerchione, R., Chiaroni, D., Del Vecchio, P., & Urbinati, A. (2020). Designing business models in circular economy: A systematic literature review and research agenda. *Business Strategy and the Environment*, *29*(4), 1734–1749.

Ching, N. T., Ghobakhloo, M., Iranmanesh, M., Maroufkhani, P., & Asadi, S. (2022). Industry 4.0 applications for sustainable manufacturing: A systematic literature review and a roadmap to sustainable development. *Journal of Cleaner Production*, *334*, 130133.

Choi, T., Kumar, S., Yue, X., & Chan, H. (2022). Disruptive Technologies and Operations Management in the Industry 4.0 Era and Beyond. *Production and Operations Management*, *31*(1), 9–31.

Cozzolino, A., & Rothaermel, F. T. (2019). Discontinuities, competition, and cooperation: Coopetitive dynamics between incumbents and entrants. *Strategic Management Journal*, *39*(12), 3053–3085.

Culot, G., Nassimbeni, G., Orzes, G., & Sartor, M. (2020). Behind the definition of Industry 4.0: Analysis and open questions. *International Journal of Production Economics*, *226*, 107617.

Denzin, N. K., & Lincoln, Y. S. (2017). *The SAGE Handbook of Qualitative Research*. SAGE Publications.

Dohale, V., Verma, P., Gunasekaran, A., & Akarte, M. (2023). Manufacturing strategy 4.0: a framework to usher towards industry 4.0 implementation for digital transformation. *Industrial Management & Data Systems*, *123*(1), 10–40.

Ehrlich, M., Wisniewski, L., & Jasperneite, J. (2015). Usage of Retrofitting for Migration of Industrial Production Lines to Industry 4.0. *KommA 2015 - Jahreskolloquium Kommunikation in Der Automation*.

Eisenhardt, K. M. (1998). Building theories from case study research. *Academy of Management Review*, *14*(4), 532–550.

Eisenhardt, K. M., & Graebner, M. E. (2007). Theory Building From Cases: Opportunities And Challenges. *Academy of Management Journal*, *50*(1), 25–32.

Elia, V., Gnoni, M. G., & Tornese, F. (2017). Measuring circular economy strategies through index methods: A critical analysis. *Journal of Cleaner Production*, *142*, 2741–2751.

Ellen MacArthur Foundation. (2013). *Transitioning to a circular economy business | Report*.

Enang, E., Bashiri, M., & Jarvis, D. (2023). Exploring the transition from techno centric industry 4.0 towards value centric industry 5.0: a systematic literature review. *International Journal of Production Research*, *61*(22), 7866–7902.

European Environment Agency. (2023). *Air pollution in Europe: 2023 reporting status under the National Emission reduction Commitments Directive*.

Fareri, S., Fantoni, G., Chiarello, F., Coli, E., & Binda, A. (2020). Estimating Industry 4.0 impact on job profiles and skills using text mining. *Computers in Industry*, *118*, 103222.

Forti, V., Baldé, C. P., Kuehr, R., & Bel, G. (2020). *The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential*. United Nations University, United Nations Institute for Training and Research – co-hosted SCYCLE Programme, International Telecommunication Union, and International Solid Waste Association Bonn, Geneva and Rotterdam.

Gallo, M., Romano, E., & Carmela, L. (2012). A Perspective on Remanufacturing Business: Issues and Opportunities. In *International Trade from Economic and Policy Perspective*. InTech.

Gebauer, H., Paiola, M., Saccani, N., & Rapaccini, M. (2021). Digital servitization: Crossing the perspectives of digitization and servitization. *Industrial Marketing Management*, *93*, 382–388.

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017a). The Circular Economy – A new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757–768.

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017b). The Circular Economy – A New Sustainability Paradigm? *Journal of Cleaner Production*, *143*, 757–768.

German Federal Government. (2016). The new high-tech strategy innovations for Germany. *Ederal Ministry of Education and Research (BMBF) Division Innovation Policy Issues*, 1–58.

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, *114*, 11–32.

Ghobakhloo, M. (2018). The future of manufacturing industry: a strategic roadmap toward Industry 4.0. *Journal of Manufacturing Technology Management*, *29*(6), 910–936.

Ghobakhloo, M. (2020). Industry 4.0, digitization, and opportunities for sustainability. *Journal of Cleaner Production*, *252*, 119869.

Ghobakhloo, M., Fathi, M., Iranmanesh, M., Maroufkhani, P., & Morales, M. E. (2021). Industry 4.0 ten years on: A bibliometric and systematic review of concepts, sustainability value drivers, and success determinants. *Journal of Cleaner Production*, *302*, 127052.

Ghobakhloo, M., Iranmanesh, M., Foroughi, B., Babaee Tirkolaee, E., Asadi, S., & Amran, A. (2023). Industry 5.0 implications for inclusive sustainable manufacturing: An evidence-knowledge-based strategic roadmap. *Journal of Cleaner Production*, *417*, 138023.

Goodall, P., Rosamond, E., & Harding, J. (2014). A review of the state of the art in tools and techniques used to evaluate remanufacturing feasibility. *Journal of Cleaner Production*, *81*, 1–15.

Govindan, K., Jiménez-Parra, B., Rubio, S., & Vicente-Molina, M.-A. (2019). Marketing issues for remanufactured products. *Journal of Cleaner Production*, *227*, 890–899.

Guerreiro, B. V., Lins, R. G., Sun, J., & Schmitt, R. (2018). Definition of Smart Retrofitting: First Steps for a Company to Deploy Aspects of Industry 4.0. In A. Hamrol, O. Ciszak, S. Legutko, & M. Jurczyk (Eds.), *Advances in Manufacturing. Lecture Notes in Mechanical Engineering* (pp. 161–170). Springer.

Holopainen, M., Saunila, M., & Ukko, J. (2023). Value creation paths of organizations undergoing digital transformation. *Knowledge and Process Management*, *30*(2), 125–136.

Jensen, J. P., Prendeville, S. M., Bocken, N. M. P., & Peck, D. (2019). Creating sustainable value through remanufacturing: Three industry cases. *Journal of Cleaner Production*, *218*, 304–314.

Kagermann, H., Wahlster, W., & Helbig, J. (2013). *Recommendations for Implementing the Strategic Initiative Industrie 4.0. Final report of the Industrie 4.0 Working Group*.

Kanda, W., Geissdoerfer, M., & Hjelm, O. (2021). From circular business models to circular business ecosystems. *Business Strategy and the Environment*, *30*(6), 2814–2829.

Khan, I. S., Ahmad, M. O., & Majava, J. (2021). Industry 4.0 and sustainable development: A systematic mapping of triple bottom line, Circular Economy and Sustainable Business Models perspectives. *Journal of Cleaner Production*, *297*, 126655.

Kipper, L. M., Iepsen, S., Dal Forno, A. J., Frozza, R., Furstenau, L., Agnes, J., & Cossul, D.

(2021). Scientific mapping to identify competencies required by industry 4.0. *Technology in Society*, *64*, 101454.

Kohtamäki, M., Parida, V., Oghazi, P., Gebauer, H., & Baines, T. (2019). Digital servitization business models in ecosystems: A theory of the firm. *Journal of Business Research*, *104*, 380–392.

Kraus, S., Durst, S., Ferreira, J. J., Veiga, P., Kailer, N., & Weinmann, A. (2022). Digital transformation in business and management research: An overview of the current status quo. *International Journal of Information Management*, *63*, 102466.

Lanzolla, G., Lorenz, A., Miron-Spektor, E., Schilling, M., Solinas, G., & Tucci, C. L. (2020). Digital Transformation: What is new if anything? Emerging patterns and management research. *Academy of Management Discoveries*, *6*(3), 341–350.

Lanzolla, G., Pesce, D., & Tucci, C. L. (2023). The digitalization of physical reality: theoretical lenses to incorporate digitalization into management research,". In C. Cennamo, G. B. Dagnino, & F. Zhu (Eds.), *Research Handbook on Digital Strategy* (pp. 83–101). Edward Elgar Publishing.

Li, A. Q., Rich, N., Found, P., Kumar, M., & Brown, S. (2020). Exploring product–service systems in the digital era: a socio-technical systems perspective. *The TQM Journal*, *32*(4), 897–913.

Liao, Y., Deschamps, F., Loures, E. de F. R., & Ramos, L. F. P. (2017). Past, present and future of Industry 4.0 - a systematic literature review and research agenda proposal. *International Journal of Production Research*, *55*(12), 3609–3629.

Linder, M., & Williander, M. (2017). Circular Business Model Innovation: Inherent Uncertainties. *Business Strategy and the Environment*, *26*(2), 182–196.

Liu, C., Zhu, Q., Wei, F., Rao, W., Liu, J., Hu, J., & Cai, W. (2019). A review on remanufacturing assembly management and technology. *The International Journal of Advanced Manufacturing Technology*, *105*(11), 4797–4808.

Lopes de Sousa Jabbour, A. B., Latan, H., Chiappetta Jabbour, C. J., & Seles, B. M. R. P. (2023). Does applying a circular business model lead to organizational resilience? Mediating effects of industry 4.0 and customers integration. *Technological Forecasting and Social Change*, *194*, 122672.

Markides, C. C. (2008). *Game-Changing Strategies. How to Create New Market Space in Established Industries by Breaking the Rules*. Jossey-Bass.

Marshall, M. N. (1996). Sampling for qualitative research. *Family Practice*, *13*(6), 522–525.

Miehé, L., Palmié, M., & Oghazi, P. (2022). Connection successfully established: How complementors use connectivity technologies to join existing ecosystems – Four archetype strategies from the mobility sector. *Technovation*, 102660.

Moldovan, L. (2019). State-of-the-art Analysis on the Knowledge and Skills Gaps on the Topic of Industry 4.0 and the Requirements for Work-based Learning. *Procedia Manufacturing*, *32*, 294–301.

Müller, J. M., Buliga, O., & Voigt, K.-I. (2018). Fortune favors the prepared: How SMEs approach business model innovations in Industry 4.0. *Technological Forecasting and Social Change*, *132*, 2–17.

Munirathinam, S. (2020). Industry 4.0: Industrial Internet of Things (IIOT). In P. Raj & P. Evangeline (Eds.), *The Digital Twin Paradigm for Smarter Systems and Environments: The Industry Use Cases* (Vol. 117, Issue 1, pp. 129–164). Elsevier.

Nayernia, H., Bahemia, H., & Papagiannidis, S. (2022). A systematic review of the implementation of industry 4.0 from the organisational perspective. *International Journal of Production Research*, *60*(14), 4365–4396.

Nosalska, K., Piątek, Z. M., Mazurek, G., & Rządca, R. (2019). Industry 4.0: coherent definition framework with technological and organizational interdependencies. *Journal of Manufacturing Technology Management*, *31*(5), 837–862.

Ochieng, P. A. (2009). An analysis of the strenghts and limitation of qualitative and quantitative research paradigms. *Problems of Education in the 21st Century*, *13*.

Oesterreich, T. D., & Teuteberg, F. (2016). Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. *Computers in Industry*, *83*, 121–139.

Omwando, T. A., Otieno, W. A., Farahani, S., & Ross, A. D. (2018). A Bi-Level fuzzy analytical decision support tool for assessing product remanufacturability. *Journal of Cleaner Production*, *174*, 1534–1549.

Ortt, R., Stolwijk, C., & Punter, M. (2020). Implementing Industry 4.0: assessing the current state. *Journal of Manufacturing Technology Management*, *31*(5), 825–836.

Ostmeier, E., & Strobel, M. (2022). Building skills in the context of digital transformation: How industry digital maturity drives proactive skill development. *Journal of Business Research*, *139*, 718–730.

Patton, M. Q. (1990). *Qualitative evaluation and research methods*. Sage.

Plattform Industrie 4.0. (2019). Shaping Digital Ecosystems Globally. *Federal Ministry for Economic Affairs and Energy (BMWi)*, 8. www.bmwi.de

Ragin, C. C. (1987). *The comparative method: Moving beyond qualitative and quantitative strategies*. University of California Press.

Ragin, C. C. (2008). *Redesigning Social Inquiry: Fuzzy Sets and Beyond.* Wiley Online Library.

Ramakrishna, S., Ngowi, A., Jager, H. De, & Awuzie, B. O. (2020). Emerging Industrial Revolution: Symbiosis of Industry 4.0 and Circular Economy: The Role of Universities. *Science, Technology and Society*, *25*(3), 505–525.

Remane, G., Hanelt, A., Nickerson, R. C., & Kolbe, L. M. (2017). Discovering digital business models in traditional industries. *Journal of Business Strategy*, *38*(2), 41–51.

Rosa, P., Sassanelli, C., Urbinati, A., Chiaroni, D., & Terzi, S. (2020). Assessing relations between Circular Economy and Industry 4.0: a systematic literature review. *International Journal of Production Research*, *58*(6), 1662–1687.

Rußmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P., & Harnisch, M. (2015). Industry 4.0. The future of productivity and growth in manufacturing industries. In *The Boston Consulting Group*.

Sahut, J., Dana, L., & Laroche, M. (2020). Digital innovations, impacts on marketing, value chain and business models: An introduction. *Canadian Journal of Administrative Sciences / Revue Canadienne Des Sciences de l'Administration*, *37*(1), 61–67.

Sakao, T., & Sundin, E. (2019). How to Improve Remanufacturing?—A Systematic Analysis of Practices and Theories. *Journal of Manufacturing Science and Engineering*, *141*(2), 021004.

Sarkar, B., Ullah, M., & Sarkar, M. (2022). Environmental and economic sustainability through innovative green products by remanufacturing. *Journal of Cleaner Production*, *332*, 129813.

Scarpellini, S., Portillo-Tarragona, P., Aranda-Usón, A., & Llena-Macarulla, F. (2019). Definition and measurement of the circular economy's regional impact. *Journal of Environmental Planning and Management*, *62*(13), 2211–2237.

Schumacher, A., Erol, S., & Sihn, W. (2016). A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises. *Procedia CIRP*, *52*, 161–166.

Seawright, J., & Gerring, J. (2008). Case Selection Techniques in Case Study Research. *Political Research Quarterly*, *61*(2), 294–308.

Shet, S. V., & Pereira, V. (2021). Proposed managerial competencies for Industry 4.0 – Implications for social sustainability. *Technological Forecasting and Social Change*, *173*, 121080.

Shi, Y., Chen, M., Qu, T., Liu, W., & Cai, Y. (2020). Digital connectivity in an innovative joint distribution system with real-time demand update. *Computers in Industry*, *123*, 103275.

Skellern, K., Markey, R., & Thornthwaite, L. (2017). Identifying attributes of sustainable transitions for traditional regional manufacturing industry sectors – A conceptual framework. *Journal of Cleaner Production*, *140*, 1782–1793.

Sony, M., & Naik, S. (2020). Industry 4.0 integration with socio-technical systems theory: A systematic review and proposed theoretical model. *Technology in Society*, *61*, 101248.

Sousa, M. J., & Rocha, Á. (2019). Skills for disruptive digital business. *Journal of Business Research*, *94*, 257–263.

Stuart, I., McCutcheon, D., Handfield, R., McLachlin, R., & Samson, D. (2002). Effective case research in operations management: a process perspective. *Journal of Operations Management*, *20*(5), 419–433.

Suárez-Eiroa, B., Fernández, E., Méndez-Martínez, G., & Soto-Oñate, D. (2019). Operational principles of circular economy for sustainable development: Linking theory and practice. *Journal of Cleaner Production*, *214*, 952–961.

Subramaniam, M., Iyer, B., & Venkatraman, V. (2019). Competing in digital ecosystems. *Business Horizons*, *62*(1), 83–94.

Sundin, E., & Bras, B. (2005). Making functional sales environmentally and economically beneficial through product remanufacturing. *Journal of Cleaner Production*, *13*(9), 913–925.

Tahiri, S. (2022). The Impact of Digitalization on Firms' Business Models: Opportunities and Limitations for Digital Leader. *Journal of Advanced Research in Leadership*, *1*(1), 13–32.

Tapaninaho, R., & Heikkinen, A. (2022). Value creation in circular economy business for sustainability: A stakeholder relationship perspective. *Business Strategy and the Environment*, *31*(6), 2728–2740.

Teece, D. J. (2010). Business Models, Business Strategy and Innovation. *Long Range Planning*, *43*(2–3), 172–194.

Teixeira, J. E., & Tavares-Lehmann, A. T. (2023). Industry 4.0: the future of manufacturing from the perspective of business and economics – a bibliometric literature review. *Competitiveness Review: An International Business Journal*, *33*(2), 458–482.

Vakola, M., Eric Soderquist, K., & Prastacos, G. P. (2007). Competency management in support of organisational change. *International Journal of Manpower*, *28*(3/4), 260–275.

van Eijnatten, F. M. (2013). Developments in socio-technical systems design (STSD). In *A Handbook of Work and Organizational Psychology* (pp. 73–100). Psychology Press.

van Loon, P., Van Wassenhove, L. N., & Mihelic, A. (2022). Designing a circular business strategy: 7 years of evolution at a large washing machine manufacturer. *Business Strategy and the Environment*, *31*(3), 1030–1041.

Veile, J. W., Kiel, D., Müller, J. M., & Voigt, K.-I. (2019). Lessons learned from Industry 4.0 implementation in the German manufacturing industry. *Journal of Manufacturing Technology Management*, *31*(5), 977–997.

Veile, J. W., Schmidt, M.-C., Müller, J. M., & Voigt, K.-I. (2021). Relationship follows technology! How Industry 4.0 reshapes future buyer-supplier relationships. *Journal of Manufacturing Technology Management*, *32*(6), 1245–1266.

Verhoef, P. C., Broekhuizen, T., Bart, Y., Bhattacharya, A., Qi Dong, J., Fabian, N., & Haenlein, M. (2021). Digital transformation: A multidisciplinary reflection and research agenda. *Journal of Business Research*, *122*, 889–901.

Vial, G. (2019). Understanding digital transformation: A review and a research agenda. *The Journal* *of Strategic Information Systems*, *28*(2), 118–144.

Vogt Duberg, J., Johansson, G., Sundin, E., & Kurilova-Palisaitiene, J. (2020). Prerequisite factors for original equipment manufacturer remanufacturing. *Journal of Cleaner Production*, *270*, 122309.

Volberda, H. W., Khanagha, S., Baden-Fuller, C., Mihalache, O. R., & Birkinshaw, J. (2021). Strategizing in a digital world: Overcoming cognitive barriers, reconfiguring routines and introducing new organizational forms. *Long Range Planning*, *54*(5), 102110.

Voss, C., Tsikriktsis, N., & Frohlich, M. (2002). Case research in operations management. *International Journal of Operations & Production Management*, *22*(2), 195–219.

Yilmaz, K. (2013). Comparison of Quantitative and Qualitative Research Traditions: epistemological, theoretical, and methodological differences. *European Journal of Education*, *48*(2), 311–325.

Yin, R. (2016). *Case study research: Design and methods*. SAGE Publications.

Zott, C., Amit, R., & Massa, L. (2011). The Business Model: Recent Developments and Future Research. *Journal of Management*, *37*(4), 1019–1042.