BEATRIZ MAKSSOUDIAN FERRAZ

ENABLING TECHNOLOGIES FOR CIRCULAR ECONOMY TRANSITION IN THE MANUFACTURING INDUSTRY

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Supervisor:
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I dedicate this work to my beloved mother, whose unwavering support guided me through life's challenges. Her love and encouragement shaped my journey. With deepest gratitude, I honor her influence on my accomplishments.

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RESUMO

A economia circular (EC) está ganhando força como uma abordagem econômica sustentável, enfatizando práticas de restauração e regeneração em vez do esgotamento de recursos. As empresas de manufatura estão adotando cada vez mais estratégias circulares para otimizar o uso de materiais e reduzir o desperdício, embora essa transição apresente desafios, especialmente na aquisição das competências necessárias. As tecnologias da Indústria 4.0 (I4.0) oferecem soluções para esses desafios, auxiliando na mudança para uma economia circular. Este estudo examina a adoção de quatro estratégias principais de EC - reuso, reparo, recondicionamento e remanufatura - no setor de manufatura por meio de uma análise abrangente e estudos de caso envolvendo 10 organizações. A pesquisa se concentra em três áreas principais: a adoção de estratégias circulares, os desafios na implementação de tecnologias I4.0 e o papel dessas tecnologias na viabilização da transição para a EC. Os resultados empíricos mostram que as organizações normalmente empregam várias estratégias circulares, sendo o reparo a mais predominante. A adoção das tecnologias I4.0 é prejudicada por vários desafios, incluindo problemas de escalabilidade, escassez de conhecimento digital e infraestrutura desatualizada. Os estudos de caso indicam que os adotantes avançados das tecnologias I4.0 se beneficiam de “delivery systems” robustos, caracterizados por abordagens econômicas e sociais abrangentes que promovem a adoção bem-sucedida da I4.0. As redes colaborativas desempenham um papel fundamental nesse sistema de fornecimento, facilitando a transferência de conhecimento e o desenvolvimento entre as partes interessadas. O estudo confirma que um nível mais alto de adoção de tecnologias de base e manufatura inteligente pode facilitar a implementação da EC, posicionando a I4.0 como um importante facilitador. A matriz de maturidade da EC e prontidão para a I4.0 desenvolvida nesta pesquisa ilustra uma clara correlação entre os investimentos em I4.0 e a maturidade da EC, ressaltando a necessidade de abordagens transformadoras em vez de melhorias incrementais para alcançar um progresso substancial. O estudo revela que as organizações identificadas como líderes em EC também emergiram como líderes em I4.0 nos estudos de caso. Essa descoberta é significativa, pois destaca a relação de interdependência entre a EC e a I4.0, sugerindo que as organizações que se destacam em uma área provavelmente se destacarão na outra. Por outro lado, os iniciantes em EC estavam mais inclinados a ter uma implementação limitada ou mínima das tecnologias I4.0, indicando uma correlação entre os níveis de maturidade da EC e a prontidão para a I4.0.

Palavras-chave: Tecnologia de fabricação avançada. Produção sustentável. Indústria 4.0

ABSTRACT

The circular economy (CE) is gaining traction as a sustainable economic approach, emphasizing restorative practices over resource depletion. Manufacturing firms are increasingly adopting circular strategies to optimize material usage and reduce waste, though this transition presents challenges, especially in acquiring the necessary competencies. Industry 4.0 (I4.0) technologies offer solutions to these challenges, aiding the shift towards a circular economy. This study examines the adoption of four key CE strategies — reuse, repair, refurbishment, and remanufacturing — in the manufacturing sector through a comprehensive review and case studies involving 10 organizations. The research focuses on three main areas: the adoption of circular strategies, challenges in implementing I4.0 technologies, and the role of these technologies in enabling CE transition. Empirical findings show that organizations typically employ multiple circular strategies, with repair being the most prevalent. The adoption of I4.0 technologies is hindered by several challenges, including scalability issues, digital expertise shortages, and outdated infrastructure. Case studies indicate that advanced adopters of I4.0 technologies benefit from robust delivery systems, characterized by comprehensive economic and social approaches that foster successful I4.0 adoption. Collaborative networks play a crucial role in this delivery system, facilitating knowledge transfer and development among stakeholders. The study confirms that a higher adoption level of base technologies and smart manufacturing can bolster CE implementation, positioning I4.0 as a key facilitator. The CE Maturity and I4.0 Readiness matrix developed in this research illustrates a clear correlation between I4.0 investments and CE maturity, underscoring the need for transformative approaches over incremental improvements to achieve substantial progress. Notably, the study revealed that organizations identified as CE Leaders also emerged as I4.0 Leaders in the case studies. This finding is significant as it highlights the interdependent relationship between CE and I4.0, suggesting that organizations excelling in one area are likely to excel in the other. Conversely, CE Beginners were more inclined to have limited or minimal implementation of I4.0 technologies, indicating a correlation between the maturity levels of CE and I4.0 readiness.

Keywords: Advanced manufacturing technology. Sustainable production. Industry 4.0

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND ACRONYMS

AGV	Automated Guided Vehicles
AI	Artificial Intelligence
AM	Additive Manufacturing
API	Application Programming Interface
BDA	Big Data and Analytics
BIM	Building Information Modeling
CAD	Computer-aided Design
CBM	Circular Business Model
CE	Circular Economy
CPS	Cyber Physical Systems
CRM	Customer Relationship Management
ERP	Enterprise Resource Planning
I4.0	Industry 4.0
I4R	Industry 4.0 Readiness
ICT	Information and Communication Technologies
IoT	Internet of Things
LE	Linear Economy
M2M	Machine-to-Machine communication
OEM	Original Equipment Manufacturer
PLA	Polylactic acid
PLC	Programmable Logic Controllers
PSS	Product Service Systems
RFID	Radio Frequency Identification
SDGs	Sustainable Development Goals
SI	Swarm Intelligence
SME	Small and medium-sized enterprises
VRPs	Value-Retention Processes
VSM	Viable System Model

CONTENTS

1 INTRODUCTION

1.1 Motivation

Circular economy and Industry 4.0 have been prominent topics in academic circles in recent years. The CE is a novel, sustainable economic model that aims to address resource constraints and climate change. It is based on the principle of 'cradle-to-cradle' rather than the linear 'take-make-dispose' approach. The CE promotes the extension of the life of products and materials in circulation through repair, reuse, remanufacturing and refurbishment processes. As such, this concept represents a significant departure from the conventional "end-of-life" concept, with an emphasis on reducing resource use and waste (BOCKEN et al., 2016). The transition from a linear economy (LE) to CE enables the decoupling of economic activity from the depletion of finite resources by creating new opportunities for business, such as value creation, revenue generation and cost reduction (MANNINEN et al., 2018).

At the same time, I4.0 is being widely adopted by academics and manufacturers due to its significant improvements in competitiveness and operational efficiency (ROSA et al., 2020). Industry 4.0 involves the use of information and communication technologies (ICT) in manufacturing systems. Its aim is to provide real-time information about production, machines, and components, integrating this information to improve decision-making, performance monitoring, and product tracking (LASI et al., 2014). However, the implementation of Industry 4.0 poses challenges for manufacturers due to skill gaps, financial constraints, and operational complexities in Industry 4.0 projects (SUNG, 2018). To overcome these challenges, a proper delivery system is needed that involves top management support and a network for knowledge and expertise sharing with research institutes (BAG et al., 2018). Additionally, there is a need for understanding what are the I4.0 adoption patterns in manufacturing companies as there is a lack of studies providing empirical evidence about the way these technologies are adopted in manufacturing context (FRANK; DALENOGARE; AYALA, 2019).

However, Industry 4.0 technologies are not only beneficial for their advantages in smart manufacturing capabilities but also because they can drive the transition towards a circular economy (JABBOUR et al., 2018). The literature discusses the relationship between CE and I4.0 from different perspectives (AGRAWAL et al., 2022). Several studies indicate that digital technologies are a strong enabler for the adoption of a circular economy, as they can support decision-making and resource management throughout the entire supply chain by enhancing tracking capabilities of product, materials, and component flows (KRISTOFFERSEN et al., 2020). However, Dubey et al. (2019) argue that there is a lack of research linking Industry 4.0 to sustainability, and even fewer studies analysing its relationship to the circular economy. Moreover, most studies have approached this relationship in a general manner, without considering the specific contributions of technology and without empirical evidence (LASKURAIN-ITURBE et al., 2021). Further empirical studies are needed to investigate the implementation patterns of digital solutions in manufacturing companies (FRANK; DALENOGARE; AYALA, 2019), as well as research on the creation of a roadmap for the adoption of Industry 4.0 in the context of CE (LASKURAIN-ITURBE et al., 2021). There is limited information available on the companies' perspectives regarding the degree of implementation of Industry 4.0 in 9R circular strategies and their impact on sustainability goals (PRAUSE; ATARI, 2017). Considering the research gaps in the literature, the following section presents the research statement and its main objectives.

This work stands as a cornerstone of the Double Degree program, pivotal in enabling the successful defense of the master's thesis at Technische Universität Darmstadt and the attainment of the Diploma de Engenheiro at Universidade de São Paulo. Conducted collaboratively across two esteemed institutions, the research unfolded from July to December 2023 at TU Darmstadt, followed by January to June 2024 at USP. Embracing the essence of international academic exchange, this thesis navigated the challenge of leveraging the distinct perspectives, methodologies, and resources offered by both universities. The investigation delved into the study of ten organizations across diverse countries, a venture made feasible by the unique opportunity presented through this dual-university endeavor. This cross-institutional collaboration not only enriched the academic journey but also broadened the research's scope and impact, ultimately contributing significantly to the advancement of knowledge in the field.

1.2 Objectives

The aim of this thesis is to investigate the implementation of four key concepts of circular economy in the manufacturing sector: reuse, repair, refurbish and remanufacture. This is achieved through a comprehensive literature review and expert interviews, which identifies any challenges that arise from the adoption of circular business models. Additionally, the study seeks to explore how Industry 4.0 technologies can potentially mitigate issues associated with the transition to a more circular economy. Based on these objectives the following research questions are posed:

RQ1: "How are the CE concepts of reuse, repair, refurbish and remanufacture implemented in the manufacturing industry?"

RQ2: "What are the primary challenges that the manufacturing industry encounters when transitioning to a circular model?"

RQ3: "Which I4.0 technologies are employed by the manufacturing industry to mitigate the challenges related to the transition to a circular model and how they can contribute to CE?"

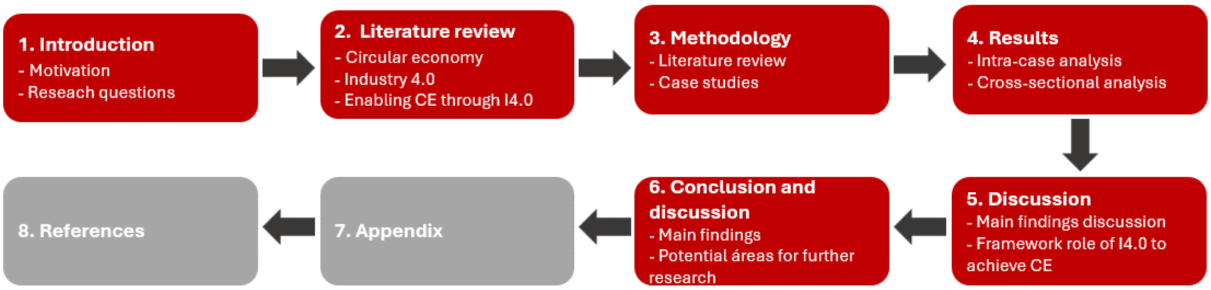
To address these questions, the literature on circular economic strategies and the role of Industry 4.0 in achieving CE are examined, and experts among manufacturing companies implementing circular business models and technologies are interviewed.

1.3 Structure

This section describes how the thesis is structured and the thesis structure is presented in the following Figure 1. In the first chapter *Introduction*, the motivation and research questions are described. The second chapter aims to create a theoretical understanding of the mains circular economy and Industry 4.0 concepts and comprehend how I4.0 technologies can enable CE transition.

At the third chapter *Methodology* the methodological approach for theoretical and practical parts are explained in the details. The next chapter *Results* presents and analyses the case studies conducted and further results are discussed. The next chapter *Discussion* discusses the empirical and theoretical findings and their significance for circular manufacturing. Moreover, a framework on the enabling role of digital technologies to achieve CE benefits is presented. Finally, the chapter *Conclusion and outlook* the main outcomes and limitations of this research are outlined and potential areas for future research to build upon this work are proposed.

Figure 1: Thesis structure



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2 LITERATURE REVIEW

In this chapter, to better comprehend the research developed so far, the theoretical foundations for circular economy and industry 4.0 are explained. The initial section introduces the concept of the circular economy and the 9R framework of circular economy approaches. In the following section the definition of Industry 4.0 is described, and the main technologies are presented. Finally, the third section illustrates how I4.0 can enable circular economy transition.

2.1 Circular economy

The global economy is predominantly guided by a linear economic model that has been widespread since the Industrial Revolution. During this period, mass production gained popularity as a low-cost strategy to improve citizens' quality of life (AZEVEDO, 2015). However, it was eventually discovered that this approach led to unintended consequences, including negative impacts on the environment. Future projections indicated problematic scenarios for future generations due to the depletion of natural resources. As a result, there was a need for a new model that could provide more sustainable and appropriate solutions for industrial development while at the same time exploiting natural resources in a controlled, efficient, and planned manner. Consequently, the linear model faced questioning, leading to the emergence of the concept of circular economy.

The CE has become a strategic and sustainable economic model that distances itself from the current linear model of extraction, transformation, use and disposal, through a different approach for production cycles (DEUTZ, 2020). Its aim is to extend the lifespan of various materials and waste by treating them as manageable resources, promoting their reusability. Circular economy comprises not only waste management but also the development, production, and consumption or utilization of a product as a secondary material.

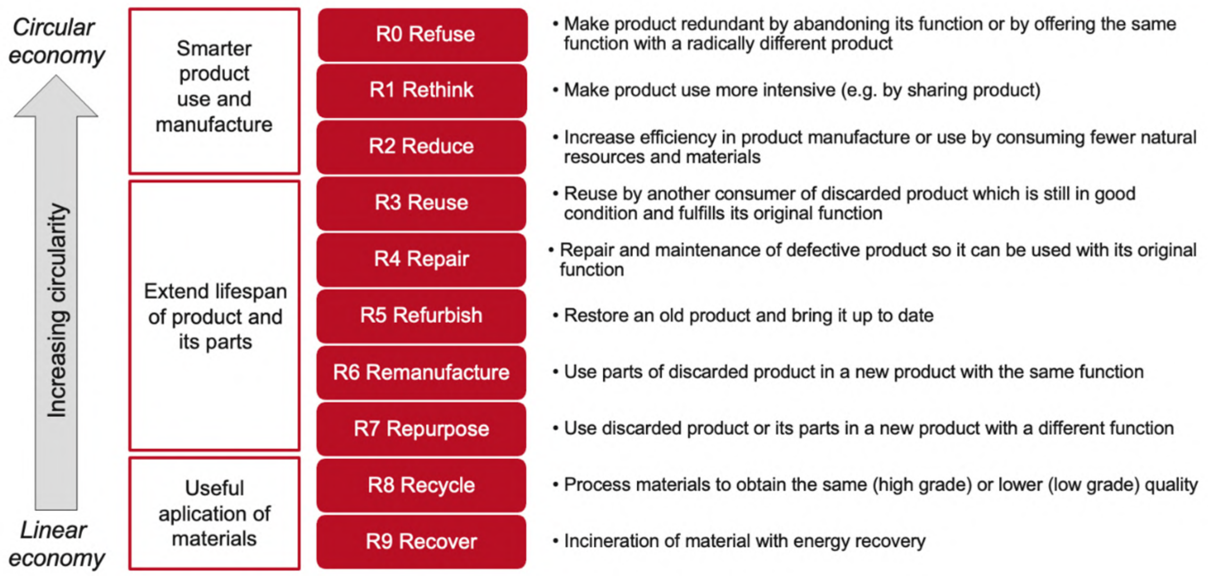
2.1.1 Circular economy strategies framework

Several strategies have been proposed to optimize the utilization and recycling of materials, while minimizing waste and maximizing their value (POTTING et al., 2017). The R-strategies have been identified as the primary framework for the transition to circularity. However, the scientific community has not yet reached a unanimous agreement on the number of R-strategies that can be included in the framework. This study adopts the 9R framework developed by Kirchherr, Reike e Hekkert (2017) as illustrated in Figure 2.

The 9R framework comprises Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover. These circular strategies are arranged in order of increasing power to achieve circularity (starting from high to low number, i.e. R9 to R0). A greater level of material circularity within a product chain can extend the lifespan of these materials and increase the likelihood of their continued use after disposal, ideally with maintained quality. This results in a reduced need for natural resources in material production for product manufacturing (POTTING et al., 2017).

The shorter the loop (lower R), the fewer external inputs are required to close it. However, greater effort is needed to implement it and the strategy becomes more circular. On the other hand, the longer the loop (higher R), the more external inputs are needed to close it, but less effort is required to implement it and the strategy becomes less circular.

Figure 2: 9R Framework



Source: Adapted from: Kirchherr, Reike e Hekkert (2017)

The R strategies can be structured into three groups. The first group includes Refuse, Rethink and Reduce (R0 - R2) strategies that enable smarter product use and manufacture. This group eliminates waste at the design phase by implementing strategies to: refuse the initial harmful product and provide a better alternative; rethink waste as a resource, thereby amplifying product use through sharing amongst different customers without purchasing it or creating a multi-functional product, and reduce the amount of raw materials required, thereby increasing product efficiency (MORSELETTO, 2020)

The second group (Reuse, Repair, Refurbish, Remanufacture and Repurpose) includes strategies to extend the lifespan of product and its parts for longer, while maintaining or improving their value. This study focuses on the Value-Retention Processes (VRPs), also known as strategies R3-R6, which are practices integrated into the technical material and product cycles of manufacturing companies (RUSSELL; NASR, 2023). R3-R7 strategies require more external inputs to work well as R0-R2 strategies, because they require "market receptivity, well-functioning reverse logistics, profitability for the parties involved, and the deployment of these strategies by varying business models" (MORSELETTO, 2020). Additionally, when applied to a product, these principles may increase stochastic uncertainty in terms of the quality and quantity of the product, posing an additional challenge for the business.

Reuse (R3) is defined as the second or subsequent use of a product that remains in good condition by another user, while retaining its original function and identity. The recovery of specific components from discarded products for reuse in other products should be included in R3. To facilitate the process of parts harvesting, products need to be designed with an easy disassembly in mind.

There are two distinct types of "reuse" that are differentiated by the type of ownership. In the first category, ownership is transferred when a previously owned product is discarded by the initial user and sold to a second user at a reduced price in a second-hand market. The second type occurs when products retain their ownership but have different users. Product service systems (PSS) fall within this category and represent a specific type of value proposition where a company offers a combination of products and services that can jointly meet the requirements of the user. The implementation of PSS is currently seen as one of the most effective tools to support the circular economy. For successful implementation, companies need to link the PSS approach with strategic and operational decisions, providing guidance on product configuration, technologies, operations, and supply chains (MENDOZA et al., 2017).

Repair (R4) is defined by Potting et al. (2017) as the repair and maintenance of a product to fulfil its intended function. The international standard EM 13306 defines maintenance as the "combination of all technical, administrative and managerial actions during the life cycle of an asset, in which it can perform its necessary function". According to this definition, postponing obsolesce (in other words, retaining a product in its working state) and reversing obsolesce (that is, restoring a product to its working state) are considered maintenance (HOLLANDER; BAKKER; HULTINK, 2017). In the 9R framework, only the second definition of maintenance is included as part of this CE strategy.

The following strategy, refurbish (R5), aims to bring an outdated product back to a satisfactory condition or meet the specified quality standards. This is achieved by replacing or restoring any major components that are damaged or at risk of failure, regardless of whether the customer has reported any issues with those components (HOLLANDER; BAKKER; HULTINK, 2017). Refurbishment is also referred to as 'light' remanufacturing because it improves product function by replacing parts but excludes disassembly.

Remanufacture (R6) is undertaken in industrial processes that involve the original equipment manufacturer (OEM) and another licensed company, which is responsible for disassembling outdated products into their components. This process is subject to rigorous testing and the remanufactured products must adhere to a set of performance specifications (HOLLANDER; BAKKER; HULTINK, 2017). A remanufactured product should have the same standard as a brand-new product, even if the components are sourced from other products and used as spare parts.

Finally, the last strategy in this group, repurpose (R7), also known as recontextualization, involves the use of discarded products or their parts to create a new product with a different function or to reuse a product for an alternative use. R7 differs from the other strategies in the group (R3-R6) because original products/parts may assume distinct identities and functions, which the other strategies in the group cannot achieve.

The Recycle (R8) and Recover (R9) strategies relate to the final category of the framework, which is the least circular group. Recycling involves processing materials to obtain recycled materials of the same or lower quality. It involves the recovery of materials from discarded items through upcycling, a process that transforms them into materials of higher quality and with improved functionality, or, conversely, through downcycling (as is the case for most materials). Upcycling is the preferred solution due to its higher value and quality, but it is often not feasible (MORSELETTO, 2020). R8 incorporates techniques such as opting for materials with high recycling rates in the production of the product, as well as the reprocessing of recycled materials into novel products (HOLLANDER; BAKKER; HULTINK, 2017).

The last and least preferred means of achieving circularity is Recovery (R9). Recovery refers to the incineration of materials that cannot be recycled with energy recovery. The disadvantage of R9 is that incineration results in the permanent destruction of materials and products, which encourages waste. Also, incineration necessitates low-cost and abundant waste to guarantee profitability, leading to competition for resources with other R solutions that are better suited for achieving circularity (MORSELETTO, 2020).

2.2 Industry 4.0

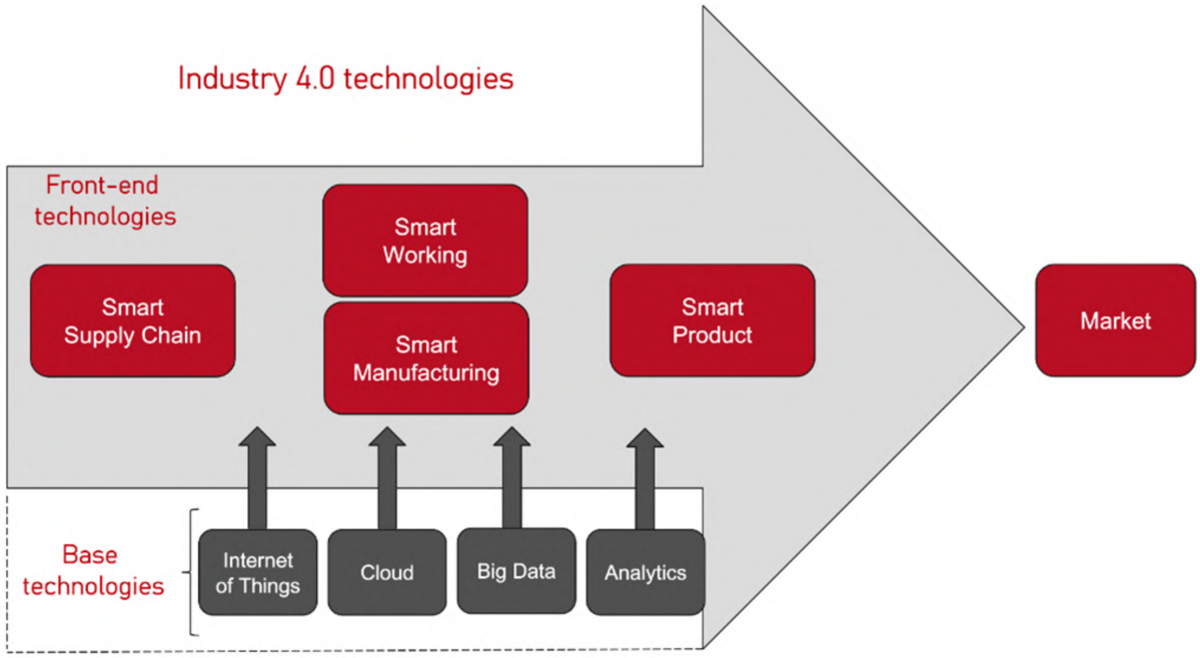
From a historical perspective, the first industrial revolution occurred in 1750 with the ground-breaking development of the steam engine, which created a new energy source that subsequently facilitated the rapid construction of railways, thereby accelerating economic growth. Later, the end of the 19th century marked the beginning of the second industrial revolution, which saw significant technological progress in various industries facilitating the development of assembly lines and mass production with the use of electricity. In the 1970s, the third industrial revolution introduced digital automation of production using electronics, information technology and industrial robotics, which contributed to the emergence of an era of high-level automation. Subsequently, systems continued to evolve and interconnect, leading to a new industrial stage in manufacturing through the integration of a range of emerging technologies to create cyber-physical systems (CPS). This marked a significant milestone at the beginning of the fourth industrial revolution (NASCIMENTO et al., 2019).

The term “Industry 4.0” was created in 2011 by a german initiative of the federal government with universities and private companies that aimed to develop advanced production systems with the aim of increasing productivity and efficiency of the national industry (KAGERMANN et al., 2013). By incorporating CPS in the manufacturing systems, companies can enhance competitiveness through different types of data acquisition and decision-making methods, facilitated by the synergistic application of Internet of Things (IoT) and information and communication technologies. Industry 4.0 enables enhanced manufacturing capabilities, and the creation of flexible and adjustable production lines for multiple products under various conditions, commonly termed Smart Manufacturing. The implementation of Industry 4.0 can yield various benefits, including enhanced quality, flexibility, and productivity. It also enables greater customization of products on a larger scale and in a sustainable manner, resulting in improved resource consumption (JABBOUR et al., 2018). Industry 4.0 technologies can be classified in various ways, and the next section outlines the conceptual framework employed.

2.2.1 Industry 4.0 framework

The adopted framework, extracted from Frank, Dalenogare e Ayala (2019), divides I4.0 technologies into two main groups based on their main objectives. The first category is called "front-end technologies" and relates to functional and market requirements as shown in Figure 3. It encompasses technologies that modify the production system (Smart Manufacturing), support the horizontal integration of the factory (Smart Supply Chain), support workers' tasks (Smart Working), and are embedded in the final products, enabling new services and solutions for customers (Smart Product). The second group of I4.0 technologies is called "base technologies" and includes technologies that enable front-end technologies by providing connectivity and intelligence for an integrated manufacturing system (WANG et al., 2016).

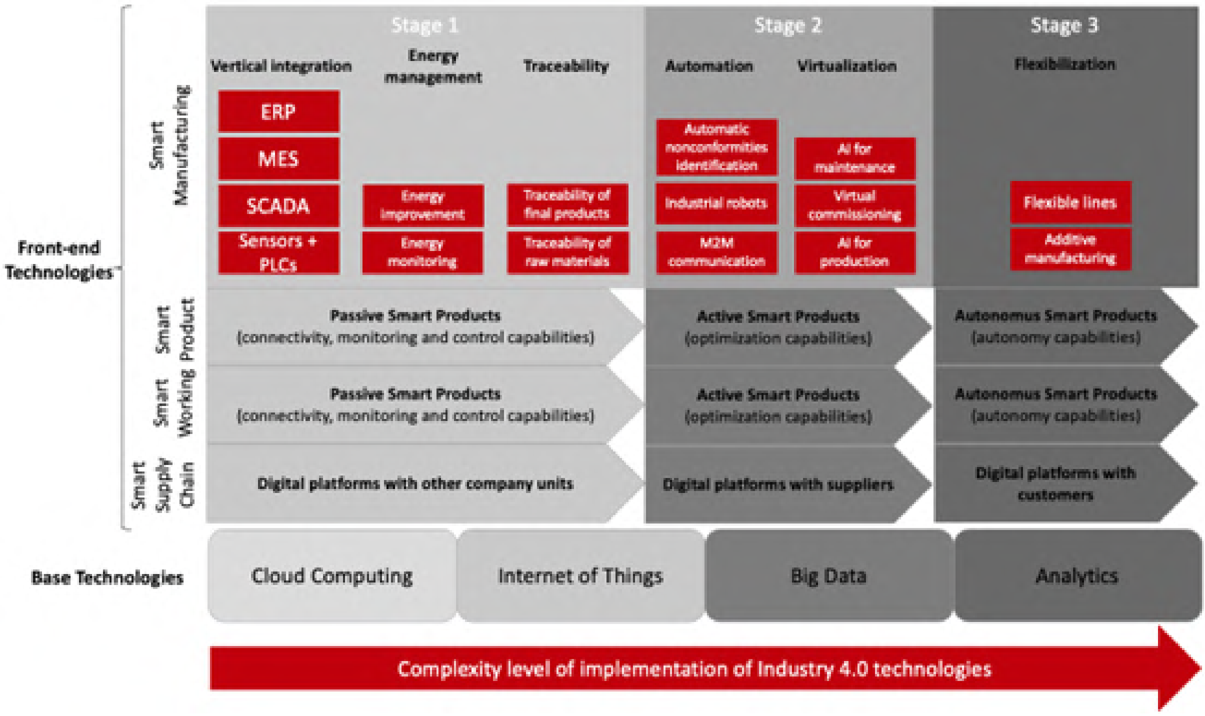
Figure 3: Theoretical framework of I4.0 technologies



Source: Adapted from: Frank, Dalenogare e Ayala (2019)

As illustrated in Figure 3, the primary and main aim of I4.0 is Smart Manufacturing, whereas Smart Products serve as an extension of this objective. Smart Manufacturing technologies can be categorized into six main categories, each serving a unique purpose, ordered by the increasing level of implementation complexity, as indicated in Figure 4: vertical integration, energy management, traceability, automation, virtualization, and flexibility (FRANK; DALENOGARE; AYALA, 2019).

Figure 4: Framework of I4.0 adoption patterns



Source: Adapted from: Frank, Dalenogare e Ayala (2019)

The first category of technologies focuses on vertical integration, the approach that enables a company to optimise all processes from the shop floor to top management, by taking control of different stages and making decisions less dependent on external factors. The implementation comprises of ICT systems such as Enterprise Resource Planning (ERP), sensors, actuators, and Programmable Logic Controllers (PLC). These systems facilitate data acquisition, transparency, and control of the entire manufacturing processes.

Smart Manufacturing also has the potential to improve energy management. Energy consumption in factories can be continuously measured and monitored using energy efficiency monitoring systems (KAGERMANN et al., 2013). By combining this information with intelligent systems, energy improvement systems can be developed to schedule intensive production stages during times with favourable electricity rates (JESCHKE et al., 2017).

The following category encompasses technologies associated with traceability, such as blockchain, radio-frequency identification (RFID) and sensors. The practice of supply chain traceability is crucial for ethical and sustainable business development. It helps to disseminate real-time information on waste at every stage of the supply chain, thereby facilitating waste reduction and optimal resource utilisation (GUPTA; KUMAR; WASAN, 2021).

Automation is also one of the main purposes of Smart Manufacturing (KAGERMANN et al., 2013). Using industrial robots, automated guided vehicles (AGVs), and machine-to-machine communication (M2M) as part of an automation system offers several benefits, such as improving quality, efficiency, productivity, and reducing waste and errors.

The following group includes virtualisation technologies that create abstractions of the physical component by using software to simulate its operation, resulting in a process that is fully transparent to both the operating system and the end user. This enables warehouse operators and managers to effectively manage increased complexity, minimize downtime and streamline operations. Processes simulation, Artificial Intelligence (AI), and virtual commissioning fall under this category.

Flexibility is a key goal of Industry 4.0. With interchangeable 3D models that can be reprogrammed to create multiple items using the same resources, additive manufacturing enables product customisation and sustainable production (FRANK; DALENOGARE; AYALA, 2019). In addition, adaptable and flexible production lines that receive information about product requirements then execute the necessary tasks to manufacture them can facilitate the manufacturing of different products in small batches with minimal productivity loss (WANG et al., 2016).

Smart product technologies refer to technological features that are incorporated into a product with the purpose of boosting its digital capabilities and services. Such features include connectivity, monitoring, control, optimization, and autonomy, which are listed in order of increasing complexity of adoption as depicted in Figure 4 (FRANK; DALENOGARE; AYALA, 2019). A notable illustration of this is the integration of sensors within a product which enable users to connect the product with other systems and monitor its condition as well as usage parameters. Smart Product technologies can generate further business opportunities for manufacturers by collecting information about product usage. This information can be used to enable the provision of digital product-service systems, whereby manufacturers can provide additional services alongside offerings of the product itself, or alternatively, provide the product as a service (AYALA et al., 2017).

The remaining two categories of front-end technologies are Smart Supply Chain and Smart Working. Frank, Dalenogare e Ayala (2019) regards them as complementary groups because they deal with operational activities rather than manufacturing and final products like Smart Manufacturing and Products. In addition, they are also considered to be front-end technologies because of their direct impact on the operational performance of the organisation.

Technologies for Smart Supply Chain comprise digital platforms that connect a company's units, suppliers, and customers in an increasingly complexity implementation order (FRANK; DALENOGARE; AYALA, 2019). Such tools assist with horizontal integration and optimize communication between manufacturers and suppliers by exchanging real-time information about product orders among internal and external stakeholders (PFOHL; YAHSI; KURNAZ, 2016).

The final group of front-end technologies is Smart Working. The first objective of this category is to increase labour productivity, which can be achieved using collaborative robots on the production line. Collaborative robots are specifically designed to interact with humans, supporting their activities in such a way that low-value-added tasks performed by workers are reduced and workers can perform more advanced tasks where collaborative robots are limited due to task flexibility and provide remote control of operations activities (BLOSS, 2016). The second objective of Smart Working technologies is to enable remote access to shop floor information, which enhances the decision-making process and visibility of the manufacturing process. Technologies such as Augmented Reality (AR) and Virtual Reality (VR) can be used to create virtual environments that aid workers in conducting maintenance procedures (FRANK; DALENOGARE; AYALA, 2019).

The second layer of I4.0 technologies, as shown in Figure 3, consists of base technologies which serve to support the other four dimensions previously described. This category includes four technologies: Internet of Things (IoT), Cloud Computing, Big Data and Analytics, which are ordered based on their level of implementation complexity. IoT refers to the integration of sensors and computing in an Internet or other communication network through wireless communication, enabling the communication of multiple objects (TAO et al., 2018). Cloud computing provides on-demand availability of computer system resources and computing power without the need for direct user management (MELL; GRANCE, 2011). This technology enables the sharing of information and coordination of tasks through the integration of devices that do not need to be physically close to each other (THOBEN; WIESNER; WUEST, 2017).

The integration of IoT and cloud computing has resulted in the development of big data technology. This is due to the high connectivity and integration of multiple devices, which allows for the extraction of large amounts of process and product data (LIU, 2013). Big data and analytics can provide significant competitive advantages in the future. They can support the self-organisation of production lines and improve decision-making activities (WANG et al., 2016). Big data is considered one of the most important drivers of Industry 4.0, as it enables the generation of digital twins in factories, and analytics can identify mistakes in production lines before they occur and improve predictive capabilities (SCHUH et al., 2020).

2.3 Enabling CE through I4.0 technologies

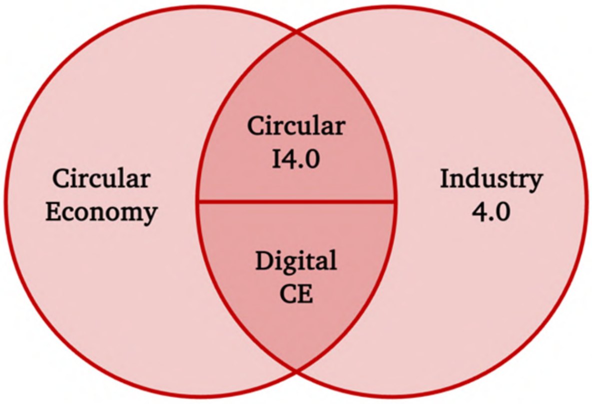
Academia widely acknowledges the positive relationship between digital technologies and CE (CHAUHAN; SHARMA; SINGH, 2021). Additionally, Bag, Gupta e Kumar (2021) point out that the degree of I4.0 adoption is positively linked to the development of 10R advanced manufacturing capabilities. However, manufacturing companies are facing difficulties in implementing Industry 4.0 due to skill gaps, limited financial resources, and operational complexities, as it is a relatively new concept (SUNG, 2018). There is also a lack of awareness surrounding Industry 4.0 and its related concepts (BAG et al., 2018).

To address these difficulties, literature indicates that the development of a robust delivery system is crucial. A strong delivery system leads to better I4.0 adoption rates and more positive outcomes in manufacturing operations (BAG et al., 2018). The delivery system is an economic and social system that can facilitate technology convergence. It includes top management support and the active creation of new models of employment, strategic plans, performance management systems and training programs to continuously improve this system. In addition, the company has established a collaborative network with suppliers, research institutes, and universities to facilitate knowledge transfer and development. The use of a delivery system raises awareness throughout the entire supply chain network, thereby reducing the risks and potential for failure in I4.0 (SUNG, 2018).

Rosa et al. (2020) identified two ways in which scholars describe the connection between CE and I4.0, as shown in Figure 5. The focus is either on the influence of I4.0 on the development of new kinds of circular business models (CBMs) or the potential benefits resulting from the digitalisation of processes, mainly in terms of innovative lifecycle management strategies.

The first perspective is Circular I4.0, which focuses on how I4.0 can improve the lifecycle management of circular products. For instance, AM is commonly associated with enabling novel methods for reintroducing recycled materials into the market. CPS is typically associated with supporting innovative services such as maintenance services, while simulation is often linked to improved management of complex supply chains, such as closed-loop systems and the remanufacturing of complex products. Big data Analytics (BDA) and IoT can be linked to CE in various ways, such as improving lifecycle management, resource exploitation, and supply chain management. Additionally, the development of circular business models can be facilitated by these technologies. The second perspective is Digital CE, which focuses on identifying the technology that best fits a specific CE-related area. For instance, BDA supports novel disassembly methods, AM facilitates innovative ways of reuse and recycling, and simulation and AM enable new forms of remanufacturing processes (ROSA et al., 2020).

Figure 5: The two hybrid categories of Circular I4.0 and Digital CE



Source: Adapted from: Rosa et al. (2020)

This framework provides guidance for management teams interested in CE and I4.0 topics. It offers two possible alternatives for implementing I4.0 in a CE context. When adopting the Circular I4.0 perspective, managers can select their CE targets and identify the most suitable tools for their strategy. When adopting the Digital CE perspective, managers can define the technologies they want to implement to support the transition to a circular economy and verify the CE performance over time (ROSA et al., 2020).

The literature is investigating how Industry 4.0 can contribute to promoting a circular economy. Many different contributions have been highlighted. The most common opportunity found in research about Industry 4.0's potential in the circular economy is the digitalisation of the circular economy, which creates opportunities for companies to improve their circular performance (JABBOUR et al., 2018). Technologies such as Additive Manufacturing (AM), Big Data and Analytics, and IoT are commonly adopted to enhance digitalisation. AM is typically associated with the digitalisation of a company's internal processes, such as the development of new manufacturing processes or managerial strategies. On the other hand, BDA and IoT facilitate digitalisation between the organisation and its manufacturing processes. BDA is typically responsible for business management, while IoT enables the development of industrial networks (ROSA et al., 2020).

A further potential positive impact of I4.0 in CE models is in product lifecycle management. Industry 4.0 enables the complete digitalisation of the product lifecycle through technologies such as digital twins. These technologies allow for real-time monitoring and analysis of product performance, which in turn enables predictive maintenance, optimal resource utilisation, and enhanced product durability. By extending the lifespan of products, companies can contribute to circular economy principles (PREUT; KOPKA; CLAUSEN, 2021). AI algorithms can be used for predictive maintenance by analyzing data from sensors, equipment, and historical maintenance records to predict when equipment is likely to fail. This enables a repair schedule to be created, preventing equipment failure and reducing downtime (TAO et al., 2018).

Industry 4.0 can improve supply chain transparency and traceability by adopting technologies such as RFID and blockchain. RFID tags can be attached to products or packaging, enabling identification and tracking. This benefits both logistics and reverse logistics processes. As a result, businesses are able to reuse, remanufacture, or recycle components of products and packaging (JABBOUR et al., 2018). Blockchain can ensure traceability of materials throughout the supply chain by providing an immutable and transparent ledger that records each transaction or movement of goods. In closed-loop systems, tracing materials is crucial for ensuring the authenticity and sustainability of products, which also assists customers and other stakeholders (HUANG et al., 2022).

Decision-making processes can also be improved through the implementation of Industry 4.0 tools such as big data and analytics. The combination of big data and analytics can enable better decision-making processes by extracting useful information from a large volume of data, identifying valuable insights and patterns to make useful predictions, and reducing the uncertainty of circular processes (BRESSANELLI et al., 2018).

2.3.1 Enabling technologies for Value Retention Processes

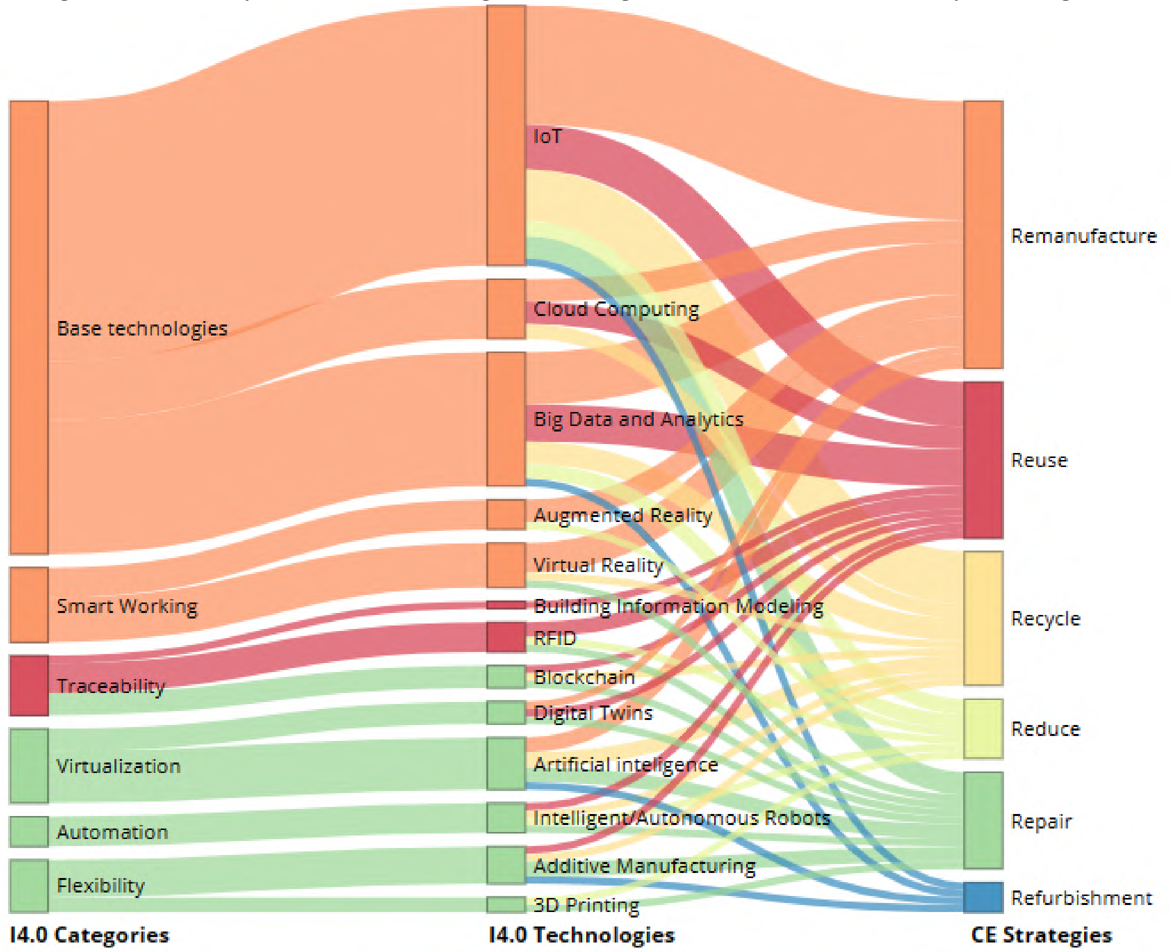
This study examines the specific ways in which individual Industry 4.0 technologies can facilitate the adoption of circular economy practices. In contrast to existing studies that examine the interaction between Industry 4.0 and the circular economy in a general manner, this study focuses on the specific potential of individual technologies to facilitate the adoption of circular economy strategies.

The objective of this session is to examine the potential of Industry 4.0 technologies to facilitate the adoption of 9R circular economy strategies, with a particular focus on product reuse, repair, refurbishment, and remanufacture. To achieve this, a comprehensive literature review was conducted to investigate the correlation between enabling technologies and circular economy strategies. A final selection of 43 articles was meticulously analysed, with key insights extracted and organised in Table 1. These insights shed light on which Industry 4.0 technologies can drive the implementation of circular economy strategies, particularly the value retention processes.

Furthermore, as illustrated in Table 1 the analysis did not identify a correlation between enabling technologies and the strategies of refuse, rethink, repurpose and recover. This suggests that these strategies have not yet been realised by currently available I4.0 technologies. Consequently, new research directions may include exploring the feasibility of applying these isolated I4.0 technologies in CE and the technical path for realising these isolated CE practices.

Following the collection of the data presented in Table 1, a Sankey chart was plotted to visualise the relationship between circular economy strategies and industry 4.0 technologies, categorised according to the framework of Frank, Dalenogare e Ayala (2019) (Figure 6). As illustrated in the chart, the most prevalent strategy observed was remanufacture, closely followed by reuse. In studies investigating the impact of Industry 4.0 technologies on circular economy practices, the strategies of reduction and recycling are often highlighted, as noted by Lei et al. (2023). However, this was not the case in this instance due to the absence of the terms “reduce” and “recycle” as research keywords, which focused solely on value retention processes. The following subssections explore the most valuable enabling technology for each value retention process.

Figure 6: Sankey chart - Enabling technologies and circular economy strategies



Source: Created by the author

2.3.1.1 Reuse strategy

The literature review indicates that the circular economy strategy of reuse is strongly supported by smart manufacturing technologies, in particular traceability technologies, and also by base technologies, as illustrated in Figure 6. One of the principal impediments to the reuse of recovered building components is the concern over the quality and performance of these components. The utilisation of digital means to support the identification, tracking, monitoring and management of building components not only provides the capacity to evaluate their physical fitness for reuse, but also opens up opportunities to introduce a range of additional services for the purpose of further quality and performance assurance (XING; KIM; NESS, 2020).

The integration of physical objects with their digital counterparts (also known as a “digital twin”) through a joint data management system allows various stakeholders to have shared access to and a common view of the life-cycle data for decision-making purposes (RIZVI; AGRAWAL; MURTAZA, 2021). The incorporation of RFID tags and digital models of building components through Building Information Modeling (BIM) provides designers with enhanced capability to track and select objects in use, each with a unique ID allotted, to incorporate into BIM models for new buildings. The BIM model is constituted by a set of data, encompassing all the building components, and their physical and functional attributes. The data provides an account of the object's state, function, and behavior under certain circumstances (XING; KIM; NESS, 2020).

Once recorded on an RFID tag, information about the object's lifespan, ownership, location, and other details can be mirrored in the BIM as attributes of that component. This record can then be stored as part of the BIM on a secure cloud-based server. Consequently, any alterations to the building components can be instantaneously reflected in the BIM through a bidirectional cyber-physical data exchange system, thereby providing consistent information support in life-cycle modelling. By integrating life-cycle data into the BIM, additional functionality is afforded to facilitate informed decision making and effective asset management strategies with regard to the potential for building components to be reused. This can be done with a high level of confidence that they are suitable for the intended purposes of application (XING; KIM; NESS, 2020).

2.3.1.2 Repair strategy

The circular strategy of repair is strongly supported by several I4.0 technologies, such as traceability, virtualisation, automation and flexibility technologies (Figure 6). Among these, traceability technologies, notably Blockchain, stand out in the literature as promising tools for the tracking and tracing of products, components and materials throughout their lifecycle. The immutable ledger provided by blockchain can be combined with IoT sensors that can track its movements and adaptations. The result is a product which brings with it a trail of dynamically-updated information housed on a blockchain, which in turn allows each user in the chain to make informed decisions about the management of materials. This information supports and facilitates repair processes, as it helps the end-user make an informed decision about how best to repair or dispose of a product and/or its components. Furthermore, this can assist manufacturers in sourcing components that a blockchain can record as recycled or remanufactured, thereby enabling companies to accurately quantify their reductions in the use of virgin materials. The detail in the stored data (accessible via QR, barcode, or RFID) allows all parties in the value chain of a product to effectively share responsibility for its material flows, thereby facilitating the practical implementation of a circular economy (CHEN; OGUNSEITAN, 2021).

In terms of virtualisation, technologies such as digital twins and artificial intelligence can also have a positive impact on the repair process. The first technology, digital twins, allows relevant information to be made available to the right actor at the right time in a decentralised manner. By using digital twins, manufacturers can create virtual models that mirror physical objects, enabling accurate simulation of repair processes and prediction of how products will behave during repair and maintenance. In addition, this virtualisation technology enables efficient testing of repair strategies and optimisation of repair processes prior to implementation by creating digital replicas of products and components that can simulate different repair scenarios in a risk-free virtual environment. This allows them to test different repair strategies, techniques and tools without the need for costly physical prototypes or real-world experimentation (PREUT; KOPKA; CLAUSEN, 2021).

The second virtualisation technology, artificial intelligence, can assist in addressing the demand for more oriented data-based decisions for repair processes. During product inspections, workers must assess the conditions of the cores, which include types of damage, severity of damage, geometric complexity and the availability of the right tools. Each incoming product exhibits different conditions and geometrical complexity, resulting in considerable uncertainty in decision-making processes. Employee decision-making for repair is influenced by a number of factors, including product features and geometry, mode and severity of damage and failure, as well as process and system capabilities. This leads to significant difficulties in assessing the product's condition. An intelligent system based on artificial intelligence can capture and utilise information and knowledge on design and process, facilitating knowledge sharing and machine learning for automation. The development of models for decision-making, prediction and optimisation can be facilitated through the application of AI techniques, resulting in a more consistent, efficient decision-making process and various improvements in the quality and reliability of products and process efficiency (YUSOH et al., 2021).

The utilisation of automation technologies, such as intelligent/autonomous robots, has the potential to revolutionise the inspection and diagnosis of equipment or products. When intelligent robots are equipped with sensors and AI algorithms, they can autonomously identify faults or defects (YUSOH et al., 2021). Furthermore, intelligent and autonomous robots can play a pivotal role in the automation of repair processes within the circular economy. This is achieved through the performance of precise and efficient repairs, disassembly, and reassembly of products. For example, the integration of robots in manufacturing and remanufacturing processes can result in enhanced production speeds and overall cost-effectiveness. This is particularly pertinent in the context of

Industry 4.0, where robotic assembly and disassembly can facilitate a circular economy by optimising material utilisation and reducing environmental impact (DANESHMAND et al., 2023).

Flexibility technologies, such as additive manufacturing and 3D printing, are promising technologies for enabling the circular strategy of repair as evidenced by the literature sample. AM is a manufacturing process that involves continuously adding material onto another material to form a product. In instances where end-of-life products are in such a deteriorated state upon collection that conventional replacement techniques cannot be employed, AM steps in to facilitate remanufacturing. This is due to the fact that AM is one of the most advanced manufacturing techniques, capable of remanufacturing complex components. The adoption of this technology is facilitating the repair processes in remanufacturing companies, particularly for components that are difficult to replace or obsolete equipment for which replacement parts may no longer be available. It allows the rapid production of customised parts tailored to specific repair needs. Instead of relying on traditional manufacturing methods that may require costly tooling or long lead times for producing specialised parts, additive manufacturing enables technicians to quickly design and fabricate custom components directly from digital models (FOFOU; JIANG; WANG, 2021).

Additive Manufacturing offers flexibility and relies on digital designs, making it suitable for modifying designs quickly during the middle-of-life phase of a product. This capability supports rapid adjustments in case of unexpected failures or changes in behaviour, as well as for repair and remanufacturing activities, especially for companies offering after-sales services. Additionally, flexibility technologies can enhance sustainability when combined with Internet of Things technology. Nevertheless, there are concerns about the current trajectory of adoption and whether the flexibility of AM components complicates end-of-life processing rather than simplifying it. Currently, there is a research agenda to evaluate issues and opportunities for achieving a circular economy. In particular, specific product characteristics such as high-value, durable, with long technology cycles and potential for leasing are cited as specific scenarios where AM could be effectively applied (KERIN; PHAM, 2019).

2.3.1.3 Refurbishment strategy

The circular strategy of refurbishment was found to be less correlated to Industry 4.0 technologies than the other value retention processes. This discrepancy can be attributed to the ambiguity surrounding the distinction of meaning between refurbishment and remanufacturing processes. Manufacturers and customers often encounter challenges in discerning between the two, as their definitions and practices overlap significantly. For instance, remanufacturing has been described using various terms such as “reconditioned”, “refurbished”, “recertified”, and so forth. This lack of clarity complicates efforts to integrate Industry 4.0 technologies into refurbishment processes and hampers the development of cohesive strategies for circular value retention (OKORIE; SALONITIS; CHARNLEY, 2021).

A review of the literature on Industry 4.0 and refurbishment and remanufacturing processes conducted by Okorie, Salonitis e Charnley (2021) revealed a significant scarcity of research on refurbishment. This suggests a potential replication of research efforts in remanufacturing and broader Industry 4.0 domains, possibly due to inconsistencies in terminology. Furthermore, the study indicated that refurbishment is likely to be the subject of research related to Industry 4.0, with a high degree of similarity to remanufacturing, given the shared characteristics of these processes. Moreover, the adoption of Industry 4.0 in remanufacturing and refurbishment is relatively recent, with research in this area only beginning a few years ago. As this integrated area of research develops, we anticipate a clearer understanding of both value retention processes (OKORIE; SALONITIS; CHARNLEY, 2021).

In the literature sample, refurbishment was correlated with the base technologies, including IoT and big data and analytics, as well as smart manufacturing technologies such as Artificial Intelligence and Additive Manufacturing. Fofou, Jiang e Wang (2021) elucidate the synergy between IoT, big data, and AI technologies that empowers smart recovery decision making systems to proactively identify and address product defects, thereby facilitating efficient refurbishment processes within the circular lifecycle supply chain. The Internet of Things facilitates real-time monitoring and data collection across the supply chain, providing crucial insights into product performance and condition. Devices equipped with IoT sensors continuously gather data on usage patterns and product metrics, enabling early detection of defects and anomalies. This proactive approach enhances refurbishment processes by allowing for timely intervention before issues escalate (FOFOU; JIANG; WANG, 2021).

Additionally, Big Data Analytics complements IoT by processing the collected data to identify patterns indicative of potential defects or inefficiencies. The analysis of historical and real-time data enables the prediction of maintenance needs and the recommendation of interventions. This proactive decision-making minimises downtime and disruptions in the supply chain, enhancing refurbishment processes by addressing defects promptly. Additionally, artificial intelligence algorithms leverage insights from IoT and big data analytics to autonomously recommend suitable actions, such as repair or refurbishment, optimising resource utilisation and extending product lifecycles within the circular economy framework (FOFOU; JIANG; WANG, 2021).

Additive Manufacturing has demonstrated its efficacy in achieving refurbishment goals by remanufacturing complex parts, particularly those retrieved from end-of-life products that traditional replacement methods are unable to address effectively. Furthermore, the integration of AI algorithms has the potential to enhance AM optimisation for refurbishment, thereby advancing the circular economy's objectives by promoting resource efficiency and product lifecycle extension (FOFOU; JIANG; WANG, 2021).

2.3.1.4 Remanufacture strategy

The circular strategy of remanufacturing was the most cited strategy related to enabling technologies in the literature sample. As illustrated in the chart, remanufacturing processes are significantly influenced by the integration of base technologies such as Internet of Things, Big Data and Analytics, Cloud Computing and Smart Working technologies. Remanufacturing processes frequently encounter difficulties associated with the discrepancy between fluctuating demand, supply, and the value of used components, which gives rise to uncertainties regarding costs and returns on investment. For instance, the disparity in the flow of information encompasses the condition, availability, and location of in-service assets (SUBRAMONIAM et al., 2021),

The literature indicates that the Internet of Things has the potential to address the aforementioned issues, as it has the capacity to facilitate communication between all objects and systems within a factory (FRANK; DALENOGARE; AYALA, 2019). By collecting and providing real-time information on remanufacturing resources, the IoT enables real-time monitoring and control, as well as continuous tracking of product conditions throughout the remanufacturing cycle (INGEMARSDOTTER et al., 2019). Furthermore, Kerin e Pham (2019) posits that the Internet of Things can facilitate remanufacturing by shortening and strengthening links between original product manufacturers, users, and remanufacturers, thereby supporting circular economy principles. The paper asserts that IoT can enhance the communication of the remanufacturer with suppliers and customers, through the acquisition of data, which ensures greater visibility of availability and quality. By combining product nominal data, such as design specification information, with performance and product status data, it may be possible to reduce risks and increase efficient resource circulation.

Furthermore, this data-driven approach can significantly enhance traceability by offering comprehensive insights into the origin, history, and current status of components. This enhanced traceability not only improves inventory management but also enhances quality control and ensures regulatory compliance. For remanufacturers, who heavily depend on such information to execute remanufacturing processes effectively, this capability is particularly crucial. With comprehensive insight into the lifecycle of components, remanufacturers are able to make informed decisions, optimise resource allocation, and guarantee the integrity and quality of remanufactured products (SUBRAMONIAM et al., 2021).

The implementation of Big Data and Analytics technologies can also confer numerous advantages upon the remanufacturing industry. As Chau et al. (2021) notes, these technologies enable remanufacturers to make informed decisions regarding product-oriented challenges, given the vast array of data at various levels. As a result, remanufacturers are better equipped to identify and engage with the most suitable customers from the extensive data pool of information about customers. In the recent past, customer service has emerged as an essential component of the remanufactured product industry. This has contributed considerably to customer satisfaction. It would be challenging to establish and maintain positive relationships with diverse customer bases. Therefore, Big Data should be employed in the customer service process as an effective method to enhance customer satisfaction when utilising remanufactured products (CHAU et al., 2021).

The literature also highlights the potential of big data to facilitate the coordination and analysis of materials information, providing crucial insights into end-of-life product characteristics, driving strategic decisions in supply chain management, cleaner production initiatives, and product lifecycle management, and improving competitiveness. Furthermore, it enables the dynamic mapping of relationships between disassembly attributes and real-time data, thereby optimising remanufacturing processes for efficiency and sustainability. Nevertheless, challenges such as constructing an end-to-end view of remanufacturing processes, standardisation, information security, and stable interfaces must be addressed in order to fully exploit big data's potential in remanufacturing (KERIN; PHAM, 2019; FOFOU; JIANG; WANG, 2021; TIWARI et al., 2021).

Cloud computing has the potential to significantly enhance remanufacturing processes by enabling efficient data collection, storage, and processing without the need for internet transmission. This has the effect of streamlining decision-making and reducing investment in database facilities. Cloud platforms are able to efficiently retrieve information on product lifespan, material categories, and recycling collection sites, which can be used to inform remanufacturing initiatives (CATERINO et al., 2022). Furthermore, cloud services facilitate stakeholder management by enabling continuous monitoring of actions and information sharing, enhancing collaboration across supply chains and benefiting remanufacturing economically, environmentally, and socially (LIU; SONG; LIU, 2023).

Smart Working technologies, such as Virtual Reality and Augmented Reality technologies, offer many opportunities to revolutionise remanufacturing processes. The first technology, VR, enables immersive disassembly planning at the product design stage, empowering designers to visualise and optimise disassembly sequences specifically tailored for remanufacturing purposes (KERIN; PHAM, 2019; CATERINO et al., 2022). Complementing VR, AR provides real-time guidance and assistance during remanufacturing tasks, enhancing efficiency and precision in disassembly, inspection, and reassembly processes. The use of AR-enabled devices enables technicians to access detailed instructions and part diagrams directly within their field of view, thereby streamlining remanufacturing operations and reducing downtime. Furthermore, the integration of VR and AR facilitates virtual testing and validation of remanufactured products, enabling engineers to identify and address potential issues at an early stage in the process, which ultimately improves product quality and accelerates time-to-market. In the field of training and workforce development, VR and AR offer the potential for interactive simulations and training modules tailored to remanufacturing tasks. This allows technicians to practise their skills in a risk-free virtual environment, thereby enhancing their proficiency in remanufacturing operations (CHAU et al., 2021).

Table 1: Enabling technologies for circular economy strategies

			Circular Economy Strategies					
	I4.0 Category	I4.0 Technology	Reduce	Reuse	Repair	Refurbishment	Remanufacture	Recycle
Enabling technologies	Base technologies	Cloud Computing		Bressanelli et al. (2018); Xing, Kim and Ness (2020); Liu, Song and Liu (2023);			Bressanelli et al. (2018); Caterino et al. (2022); Liu, Song and Liu (2023);	Liu, Song and Liu (2023); Ghiaci and Ghoushchi (2023);
		Internet of Things	Massaro et al. (2021); Awan, Stroufe and Shabaz (2021);	Bressanelli et al. (2018);Ingemarsdotter et al. (2019); Cwiklicki and Wojnarowska (2020); Xing, Kim and Ness (2020); Awan, Stroufe and Shabaz (2021); Taddei (2022);	Awan, Stroufe and Shabaz (2021); Fofou, Jiang and Wang (2021); Tiwari et al. (2021);	Fofou, Jiang and Wang (2021);	Bressanelli et al. (2018); Ingemarsdotter et al. (2019); Kerin and Phan (2019); Awan, Stroufe and Shabaz (2021); Chau et al. (2021); Fofou, Jiang and Wang (2021); Laskurain-Iturbe et al. (2021); Subramoniam et al. (2021); Tiwari et al. (2021); Caterino et al. (2022); Delpla, Kenné and Hof (2022); Taddei (2022); Sun and Wang (2022);	Ingemarsdotter et al. (2019); Cwiklicki and Wojnarowska (2020); Massaro et al. (2021); Awan, Stroufe and Shabaz (2021); Fofou, Jiang and Wang (2021); Sun and Wang (2022); Ghiaci and Ghoushchi (2023);
		Big Data and Analytics	Massaro et al. (2021); Laskurain-Iturbe et al. (2021);	Bressanelli et al. (2018); Nascimento et al. (2019); Cwiklicki and Wojnarowska (2020); Fofou, Jiang and Wang (2021); Laskurain-Iturbe et al. (2021);		Fofou, Jiang and Wang (2021);	Bressanelli et al. (2018); Kerin and Phan (2019); Chau et al. (2021); Fofou, Jiang and Wang (2021); Laskurain-Iturbe et al. (2021); Tiwari et al. (2021); Ghiaci and Ghoushchi (2023);	Cwiklicki and Wojnarowska (2020); Fofou, Jiang and Wang (2021); Laskurain-Iturbe et al. (2021);
	Smart Manufacturing Traceability	Building Information Modeling		Xing, Kim and Ness (2020)				
		Blockchain		Chen, Despeisse and Johansson (2020);	Chen, Despeisse and Johansson (2020);	Chen, Despeisse and Johansson (2020);	Chen, Despeisse and Johansson (2020); Subramoniam et al. (2021); Tang et al. (2022);	Tang et al. (2022);
		RFID	Massaro et al. (2021);	Xing, Kim and Ness (2020); Rizvi, Agrawal and Murtaza (2021);	Rizvi, Agrawal and Murtaza (2021);		Kerin and Phan (2019); Rizvi, Agrawal and Murtaza (2021);	Massaro et al. (2021);
	Smart Manufacturing Automation	Intelligent/ Autonomous Robots	Laskurain-Iturbe et al. (2021);	Daneshmand et al. (2023);	Tiwari et al. (2021);		Kerin and Phan (2019); Subramoniam et al. (2021); Tiwari et al. (2021); Daneshmand et al. (2023);	Daneshmand et al. (2023);
		Drones					Subramoniam et al. (2021);	
	Smart Manufacturing Virtualization	Artificial Inteligence			Fofou, Jiang and Wang (2021); Yusoh et al. (2021);	Fofou, Jiang and Wang (2021);	Fofou, Jiang and Wang (2021); Subramoniam et al. (2021);	Fofou, Jiang and Wang (2021); Ghiaci and Ghoushchi (2023);
		Cyber Physical Systems		Xing, Kim and Ness (2020);			Caterino et al. (2022); Ghiaci and Ghoushchi (2023);	
		Digital Twins		Tiwari et al. (2021);	Tiwari et al. (2021);		Tiwari et al. (2021);	Tiwari et al. (2021);
	Smart Manufacturing Flexibility	Additive Manufacturing	Nascimento et al. (2019); Laskurain-Iturbe et al. (2021);	Laskurain-Iturbe et al. (2021);	Kerin and Phan (2019); Fofou, Jiang and Wang (2021);	Fofou, Jiang and Wang (2021);	Kerin and Phan (2019); Fofou, Jiang and Wang (2021); Laskurain-Iturbe et al. (2021); Subramoniam et al. (2021);	Laskurain-Iturbe et al. (2021);
		3D Printing	Kerdlap, Low and Ramakrishna (2019);		Bressanelli et al. (2018);			
	Smart Working	Virtual Reality	Laskurain-Iturbe et al. (2021);		Tiwari et al. (2021);		Kerin and Phan (2019); Chau et al. (2021); Subramoniam et al. (2021); Caterino et al. (2022);	Laskurain-Iturbe et al. (2021);
		Augmented Reality	Laskurain-Iturbe et al. (2021);				Kerin and Phan (2019); Chau et al. (2021); Subramoniam et al. (2021);	Laskurain-Iturbe et al. (2021);

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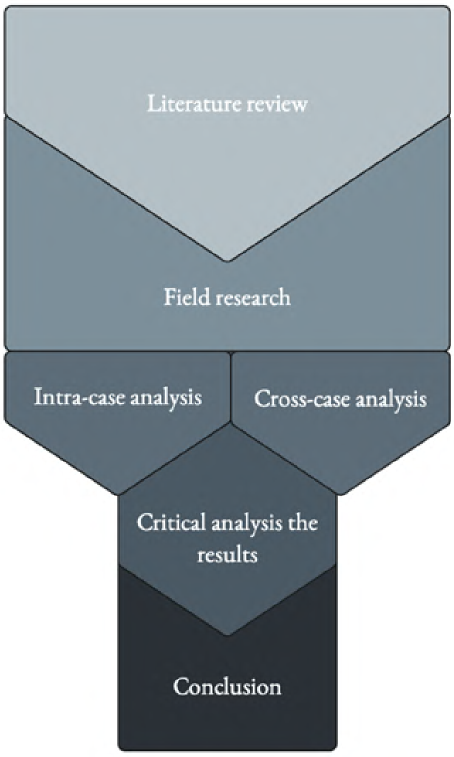
3 METHODOLOGY

The purpose of this chapter is to explain the methodology used to address the questions proposed by this research. The study aims to examine from both theoretical and practical perspectives the implementation of four circular economy concepts in the manufacturing sector and to identify technologies adopted. To achieve this, a methodological approach consisting of literature review and field research has been developed as seen in Figure 7.

Figure 7: Methodology structure

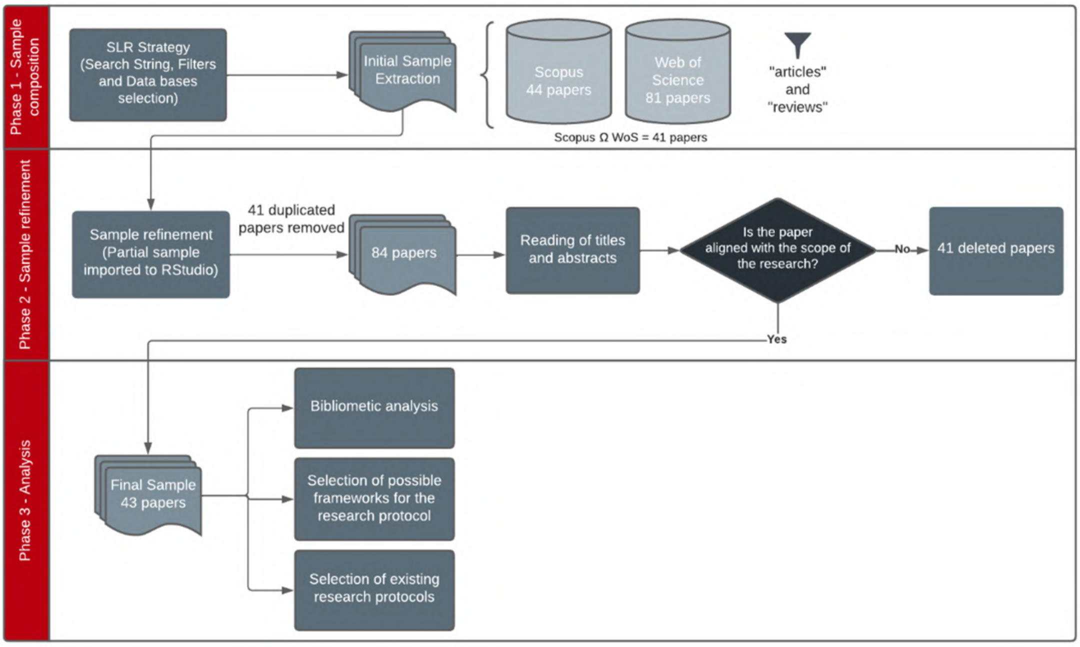


Source: Created by the author

3.1 Systematic literature review

A systematic literature review was chosen as the methodology for this study due to its ability to summarise existing literature in a transparent and easily replicable manner, providing answers to specific scientific questions. The review aimed to impartially study the implementation of four key circular economy design strategies (repair, reuse, remanufacturing, and refurbishment) within the manufacturing sector, and to ascertain how Industry 4.0 technologies can aid the resolution of issues linked to the shift towards a more circular economy. The entirety of the research process is outlined in Figure 8.

Figure 8: Systematic literature review workflow



Source: Created by the author

3.1.1 Sample composition

The search bases used for keyword searches were Web of Science and SCOPUS, selected for their reputation for quality and quantity of publications. Additionally, Web of Science includes journals listed in the Journal Citation Report (JCR) within its search engines (CARVALHO; FLEURY; LOPES, 2013), whilst SCOPUS is the biggest base of peer-reviewed publications (MORIOKA; CARVALHO, 2016). Both databases offer the advantage of collecting metadata, including articles' abstracts, references, citation indexes, authors, institution, and countries. These aspects enable the bibliometric analysis (CARVALHO; FLEURY; LOPES, 2013).

After the selection of the search bases, the main keywords were selected related to the research questions to be addressed. The searches were made in August 2023. As a result, the following groups of words were delineated for the research, which were related with the main objectives of the research:

"circular"

AND reuse OR repair OR remanufacture OR refurbishment

AND "industr* 4*" OR "digital transformation"

This search string was utilised as a "topic" in the Web of Science and the exact same search string was employed in Scopus for "article title, abstract and keyword" searches. As a result, an initial sample of 91 documents was obtained in the Web of Science database and 68 in Scopus. The sample was then filtered by document types, selecting only articles and reviews, resulting in a total of 81 items in the Web of Science and 44 in Scopus.

3.1.2 Sample refinement

To combine these two search databases and eliminate duplicate articles. R studio statistical computing environment was used, and 41 duplicated articles were removed, leading to a sample with 84 articles.

After that, the sample was closely analysed to identify articles that weren´t aligned with the scope of this research by reading the titles and abstracts and evaluating to the exclusion criteria. At this stage, 41 items (48%) were excluded from the sample, 40 of them were excluded, because they addressed industry sectors not relevant to this research, for example construction and agri-food industry. Additionally, 1 article was removed due to language inconsistencies. Consequently, the literature sample was redefined with 43 articles as the final analysis sample.

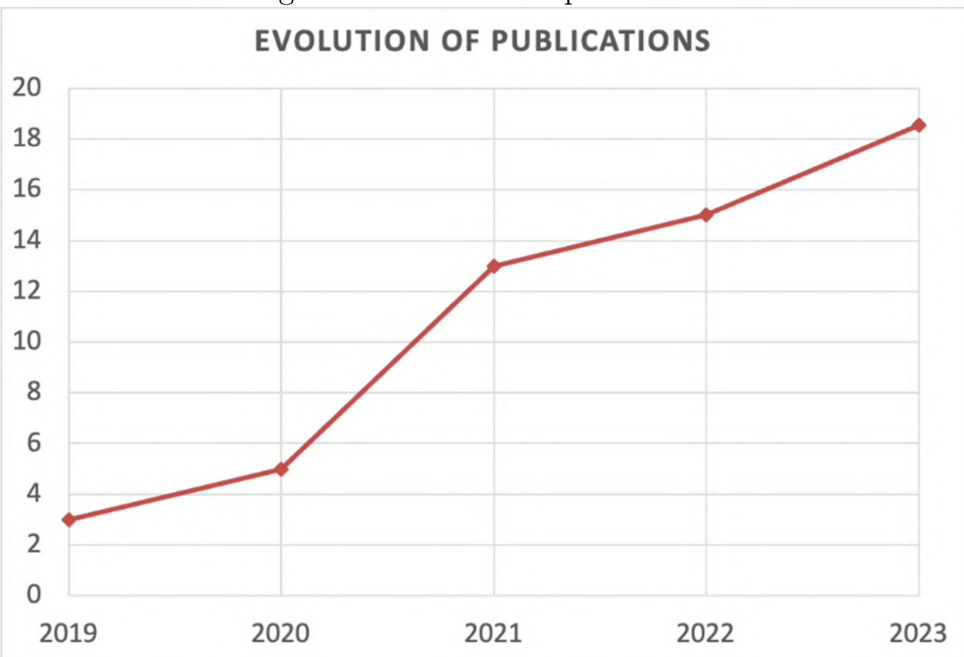
3.1.3 Analysis

After completing the sampling process, the final sample of 43 articles was subjected to a bibliometric analysis. The analysis was conducted using the Bibliometrix R package, which offers a range of tools for quantitative bibliometric research (ARIA; CUCCURULLO, 2017). Bibliometrix employs metadata including title, abstract, keywords, country and publication date, authors, citation count and facilitates a thorough science mapping analysis. This method identifies research topic trends and shifts and generates structure and network maps of the sample.

The sample spanned from 2019 to 2023, with prominent academic journals publishing on enabling technologies for circular economy transition being Business Strategy and the Environment, Sustainability (Switzerland), and Journal of Cleaner Production. These journals hold evident providence in academia, with respective impacts in Journal Citation Report (JCR) of 13.4, 3.9, and 11.1.

To demonstrate the increasing significance of the studied subject, it was conducted a study on the evolution of publications. This was achieved through the examination of the number of articles published annually on the research topic. Figure 9 illustrates the graph generated from the final selection of articles.

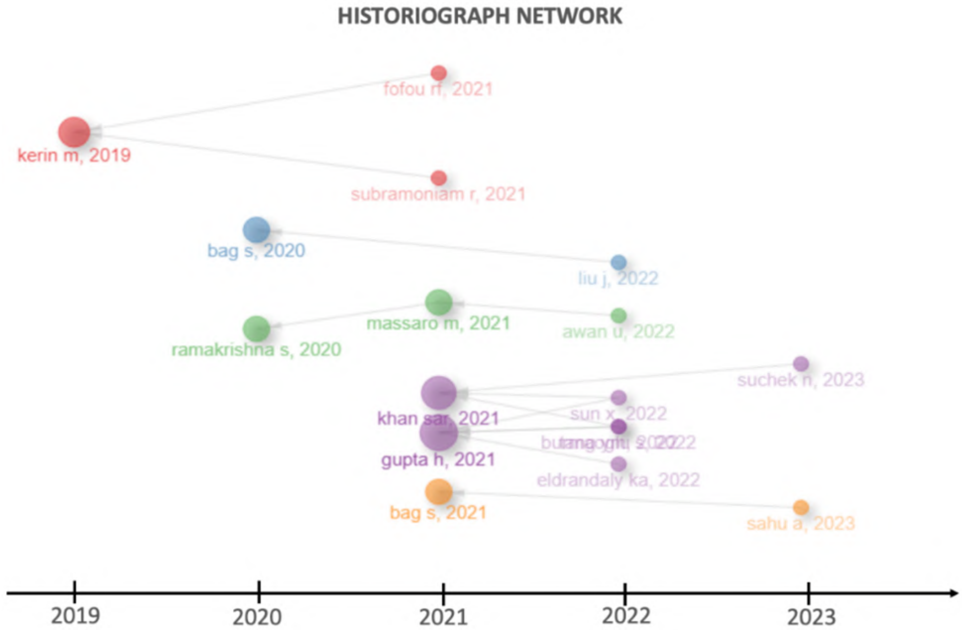
Figure 9: Evolution of publications



Source: Created by the author

The next step was plotting the bibliometric historiograph. This map initially generates the historical direct citation network from the most cited papers and subsequently displays the network in chronological order (GARFIELD, 2004). The historiograph network (Figure 10) illustrates multiple clusters of papers that are not interconnected, suggesting that the research topic is still in its infancy and not fully developed.

Figure 10: Historiograph network



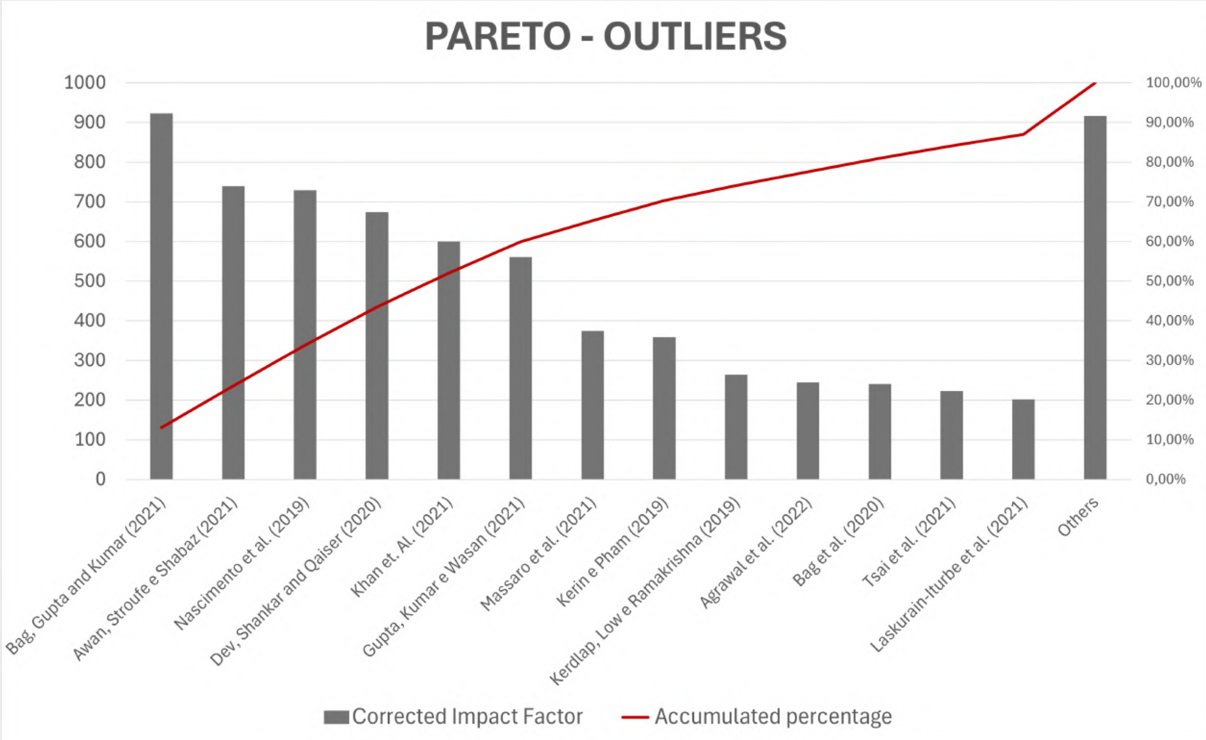
Source: Created by the author

To determine the most pertinent articles in the sample based on citation scores, we computed the corrected impact factor (CIF) of each item by applying the method introduced by Carvalho, Fleury e Lopes (2013). This indicator considers the average number of citations per year (A) of each article as well as the journal impact factor of publication (JIF), which may be accessed via the “Journal Citation Reports” section of the “Web of Science” platform. The Journal Citation Report from 2022 was utilized. The CIF was calculated as follows:

$$\text{CIF} = \text{A} * (\text{JIF} + 1)$$

After performing the necessary calculations, a pareto chart (Figure 11) was generated to detect outliers that signify the most notable articles from the sample. The analysis led to the identification of 13 outliers that were analysed in detail as shown in Table 2.

Figure 11: Pareto plot for outliers' detection



Source: Created by the author

Table 2: 13 outliers detected

Outliers	Average citation	JIF 2022	CIF	Accumulated percentage
Bag, Gupta and Kumar (2021)	71,0	12,0	923,0	13,1%
Awan, Stroufe and Shabaz (2021)	51,3	13,4	739,2	23,6%
Nascimento et al. (2019)	84,8	7,6	729,3	33,9%
Dev, Shankar and Qaiser (2020)	47,5	13,2	674,5	43,5%
Khan et. Al. (2021)	41,7	13,4	600,0	52,0%
Gupta, Kumar e Wasan (2021)	46,3	11,1	560,6	60,0%
Massaro et al. (2021)	26,0	13,4	374,4	65,3%
Kerin e Pham (2019)	29,6	11,1	358,2	70,3%
Kerdlap, Low e Ramakrishna (2019)	18,6	13,2	264,1	74,1%
Agrawal et al. (2022)	17,0	13,4	244,8	77,6%
Bag et al. (2020)	21,5	10,2	240,8	81,0%
Tsai et al. (2021)	15,7	13,2	222,5	84,1%
Laskurain-Iturbe et al. (2021)	16,7	11,1	201,7	87,0%

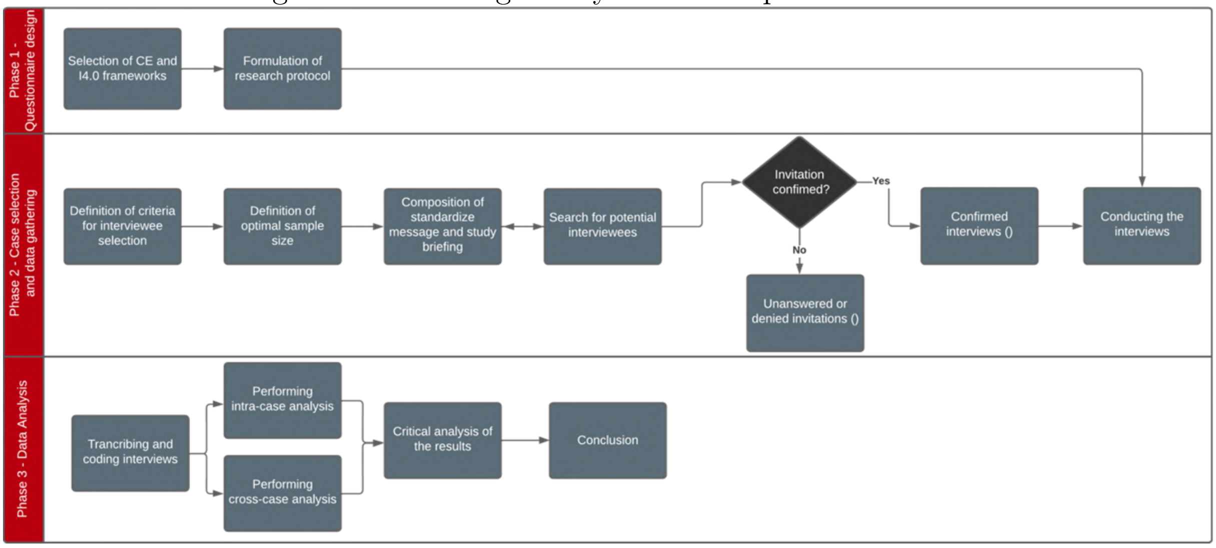
Source: Created by the author

3.2 Case studies

The systematic literature review was used as input of the second part of this study, the multiple case studies, by assisting in identifying a gap in the research, as well as proposing research questions to address this gap (EISENHARDT, 1989). Despite the recent increase in attention towards this topic, the applicability of CE literature remains limited

(LASKURAIN-ITURBE et al., 2021). Therefore, the primary objective during this stage was to gain a practical perspective on the subject to close the identified gap, while adhering to literature recommendations for developing the research protocol (EISENHARDT; GRAEBNER, 2007). Experts within manufacturing companies, who implement circular business models and develop products using circular economy approaches, were interviewed to investigate the technologies used to overcome challenges in transitioning to a circular approach. The overview of the methodology of the multiple case studies is shown in Figure 12.

Figure 12: Building theory with multiple case studies



Source: Created by the author

3.2.1 Questionnaire design

The first step to develop theory based on case studies is having a precise definition of the research questions (EISENHARDT, 1989; VOSS; TSIKRIKTSIS; FROHLICH, 2002). To provide a specification for the significant constructs of CE and Industry 4.0, two conceptual frameworks were adopted, one for CE and another for I4.0. The CE model chosen was the 9R Framework obtained from Kirchherr, Reike e Hekkert (2017) since this paper is well-regarded and widely cited in the literature. The industry 4.0 framework, adopted by Frank, Dalenogare e Ayala (2019), aided in structuring and formulating the inquiry about enabling technologies. This paper was selected for its excellent framework of I4.0 technologies developed for the manufacturing industry context, that categorizes Industry 4.0 technologies into base and front-end technologies.

The formulation of the interview protocol constituted the second step, involving self-generated elaboration questions based on the selected frameworks as well as those taken from other research protocols from Bressanelli, Perona e Saccani (2019) and Nascimento et al. (2019). This protocol was integral to enhancing both the reliability and validity of the case studies. Also, the focus of this methodology is not to influence the interviewee's responses, but to capture their perspective on the issue. However, a semi-guided questionnaire was developed to explore the main aspects of each interviewee's experience of digital technology adoption for circular economy transition and to assist the interviewer.

The interview protocol can be found in detail in Appendix A, and it is divided into six central phases as shown in Table 3. The protocol was formulated in both English and Portuguese because three interviews were carried out in Portuguese.

Table 3: Research Interview Phases and Goals

Phase	Content/Goal
Phase 0: Presentation and general instructions	- introduction of the research topic and objectives, general instructions. - presentation of the confidentiality agreement.
Phase 1: General questions about the company	- identification of the main activities of the company, size, and role of the interviewee in the company. - identification of the scope and motivation of the CE project carried out.
Phase 2: Questions about the CE project carried out	- assessment of the level of CE adoption in the company and the relative importance of circular manufacturing compared to other manufacturing capabilities. - identification of circular economy strategies from the 9R framework adopted by the company.
Phase 3: Questions on CE challenges	- recognition of the challenges faced by the company. - recognition of core skills required to meet the challenges. - recognition of key benefits gained from the implementation of the CE project. - identification of the role of digitalization in the CE project.
Phase 4: Questions about enabling technologies adoption	- assessment of the level of I4.0 technologies adoption in the company. - identification of base technologies adoption. - identification of Smart Manufacturing technologies adoption and the purpose of these adoption. - recognition of product´s capability improvement. - identification of Smart Working technologies adoption. - identification of Smart Supply Chain technologies adoption. - identification of possible future technologies adoption.
Phase 5: Final questions and conclusion	- assessment on how technologies can be used to attain CE. - identification of partners along the supply chain that help make the business viable. - finalization of the interview and elucidation of remaining questions.

Source: Created by the author

3.2.1.1 Case selection and data gathering

The process of sampling the case studies relied on seeking instances that enhanced the comprehension of the integration of circular economy principles within their products and the key technologies employed, while also providing access to stakeholders and pertinent documents that elucidated the subject in the context of the research (EISENHARDT; GRAEBNER, 2007).

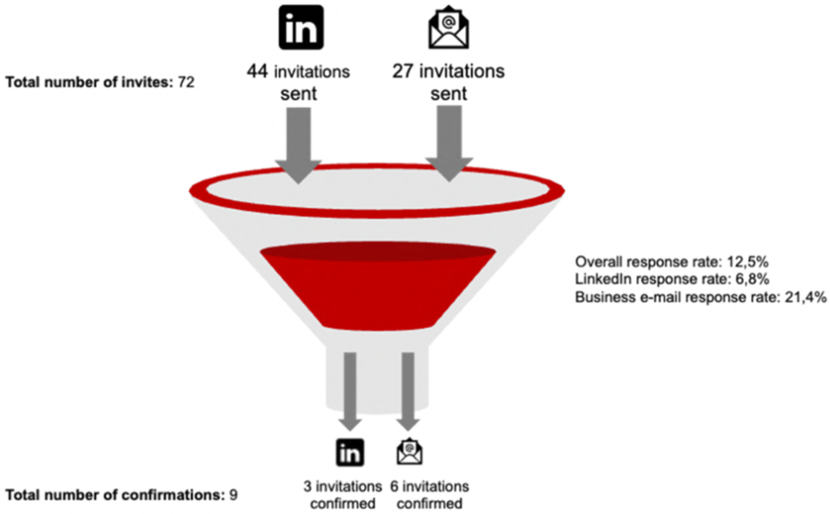
The first step in case selection was to define the requirements for the selection of case studies. A judgmental sampling technique was used to select the potential companies according to 2 criteria. First, the company should belong to the manufacturing sector. Second, the company should have carried out a CE project involving reuse, repair, refurbish or remanufacturing strategies.

The second step was to determine an optimal sample size. The literature recommends four to ten cases as an optimal number. With more than ten cases, the volume of data and complexity can become a challenge to manage, while fewer than four cases are often unconvincing and insufficient for theory building (EISENHARDT, 1989). In this study, each interview is treated as a separate case and a total of 10 interviews were conducted.

After that, to contact potential interviewees in a standardized manner, a standardized message and study briefing (see Appendix B and C) were composed in both English and German before sending the invitations. Based on the two pre-defined criteria, experts in the manufacturing sector were reached out through business email and the employment-focused social media platform, LinkedIn. LinkedIn was chosen due to the limited number of known contacts, and its effectiveness in finding professionals and companies that meet the requirements of the study. Relevant search terms such as “Circular Economy” and “Sustainability” were used to conduct the search.

The invitation phase lasted 2 months, from the end of August to the beginning of November. In total, 72 professionals were approached with this initial message (44 via LinkedIn and 27 via email addresses), resulting in 9 individuals agreeing to participate in the interview (3 via LinkedIn and 6 via email). Therefore, the overall response rate was 12,6%, which indicates that professionals were reluctant to participate in the study. Also as seen in Figure 13 the business e-mail approach (response rate: 21,4%) was significantly more successful than the LinkedIn approach (response rate: 6,8%).

Figure 13: Funnel research invites



Source: Created by the author

The names of the companies were kept confidential, and Table 4 brings an overview of the organisations to which the 10 interviewees belong. The interviews were conducted via video conference and the interviewees held different positions within their respective companies. A research protocol was utilized for each interview, which lasted approximately 37 minutes. Following transcription, the interview scripts were coded. Additionally, supplemental materials provided by the companies, such as their websites, were consulted for secondary sources.

Table 4: Overview of the interviews

ID	Sector	Core product	Organization size	Country	Interviewer role	Language
ELECTRO1	Electronics and ICT	Laptops	Large company (over 250 employees)	United Kingdom	Sustainability leadership	English
ELECTRO2	Electronics and ICT	Laptops	Large company (over 250 employees)	Germany	Corporate responsibility role	English
ELECTRO3	Electronics and ICT	Laptops	Large company (over 250 employees)	Brazil	Corporate responsibility role	Portuguese
ELECTRO4	Electronics and ICT	Drivetrain and battery systems	Large company (over 250 employees)	Germany	Specialized role in Circular Economy	English
ELECTRO5	Electronics and ICT	Laptops, printers, cartridges and toners	Large company (over 250 employees)	Brazil	Director research institute	Portuguese
HOUSE1	Household appliances	Fridges, microwaves and dishwashers	Large company (over 250 employees)	Sweden	Corporate responsibility role	English
HOUSE2	Household appliances	Washing machines, dishwashers and fridges	Large company (over 250 employees)	Germany	Project management role	English
FURNI1	Furniture	Office chairs, tables, sofas	Large company (over 250 employees)	United Kingdom	Sustainability leadership	English
FURNI2	Furniture	Mattress	Large company (over 250 employees)	Germany	Specialized role in Circular Economy	Portuguese
PILOT	University	Scooter and mobile working hub	Small organization (10 to 49 employees)	Germany	Academic researcher	English

Source: Created by the author

3.2.2 Data Analysis

The initial stage of data analysis involved transcribing and coding all the interviews conducted. Following this, an intra-case analysis was conducted, providing a detailed account of the implementation of circular strategies as well as the challenges and capabilities developed. Once the intra-case analysis was completed, the cross-case analysis for the 10 organisations was created. During the cross-case analysis, the objective was to recognise similarities, differences, and patterns among the examined organisations. The outcomes of these investigations are in the following section.

4 RESULTS

This chapter presents the description and analysis of the 10 examined case studies (Section 3.2.1). First, an intra-case analysis presents, for each organisation, the Circular Economy initiative undertaken, the challenges faced, and the enabling technologies adopted to overcome them. Next, the results from the cross-sectional analysis of the cases are presented.

4.1 Intra-case analysis

The initial five cases, namely ELECTRO1, ELECTRO2, ELECTRO3, ELECTRO4 and ELECTRO5, pertain to the Electronic and ICT sector. The two following cases, HOUSE1 and HOUSE2, pertain to the household appliances industry, while FURNI1 and FURNI2 fall under the furniture sector. The final case study is a pilot case named PILOT, conducted in a learn factory at a university.

4.1.1 Case study ELECTRO1

Company ELECTRO1 is a B2B 30-year-old enterprise that transitioned to a remanufacturing company 8 years ago. Their main goal is to create a more ethical, sustainable and socially responsible way to purchase IT devices. The core product is remanufactured laptops from premium brands. Operating in the United Kingdom, it has become a benchmark in the field with its remanufacturing processes. The company has been awarded a BSI Kitemark certification by the British Standards Institution, stating that their circular products are as good, if not better than new items. This serves as a significant incentive for other companies to reconsider their carbon agenda.

The electronics and ICT sector is widely acknowledged for its linear and rapid progress, and large manufacturing enterprises significantly contribute to carbon emissions. As stated by the interviewee, the production phase accounts for 85% of the total carbon emissions in a new laptop. If companies invested in reducing the production of new devices and utilized circular economy strategies such as repair, reuse, remanufacture, and refurbishment, they could significantly reduce carbon emissions. According to the interviewee, this approach could decrease carbon emissions by approximately one-third of a ton.

The company manufactures a considerable quantity of remanufactured and refurbished laptops, and boasts an employee count of approximately 500 individuals, of which 80% are engineers. This significant number of specialists is deemed necessary, as the company, being a remanufacturer, unfortunately, cannot access the original laptop designs, as this privilege is limited to the original manufacturers. Therefore, reverse engineering the product is a highly labor-intensive task that necessitates manual checking and evaluation by a large workforce to ensure that each project meets or exceeds the latest industry standards.

The remanufacturing processes takes about 5 or 6 hours per laptops, has a 360-point quality check and it is divided in ten steps that include initial inspection, disassembly, component inspection, remediation, replacement and upgrades, reassembly, testing, visual inspection and BSI Kitemark certified processes. Also, the company implemented a refurbished laptops line, since there was a market need for cheaper products and refurbished products are cheaper by design. In the refurbished processes, 20 minutes are spent per laptop.

ELECTRO1 has experienced several challenges. First, the alteration in customer behaviour presented a challenge, as the trend of purchasing remanufactured laptops instead of new ones is not commonly followed by many companies. The company has implemented numerous initiatives aimed at educating potential customers, as demonstrated by the following excerpt:

> *"Changing customer behaviour is massively difficult, and we strive hard to make a difference every day. We conduct workshops with educational themes, but we do not focus on the laptop itself. The laptop is a tool that enables us to communicate with people like you and perform our job. Our main objective is to raise awareness on whether it is acceptable to leave an unhealthy footprint in the workplace. Our aim is to engage with others and encourage a change in behaviour through education."*

The second challenge faced was the commonly perception that remanufactured and refurbishment products are worse than brand new items. Customers often believe that they must purchase a new device when disposing of an old one because they assume that a remanufactured device would have lower performance than a new one. However, this is a misconception. Once customers understand the benefits that can be achieved through the circular option, they may opt not to purchase a new device. Therefore, focusing on educational initiatives can contribute to the change of this perception.

To implement their business ELECTRO1 had to development some capabilities. The first thing was to invest in innovation through R&D initiatives, remanufacturing a brand-new device that the company originally didn't produce into a device that is fully functional and as good as it previously was or even better. Also, these innovative processes had to be market-tested to ensure that the new technologies developed were not falling apart, and these would lead to customers compromising, which the company tries to avoid at most. Another aspect that ELECTRO1 required to realise their circular business model was the establishment of their own factory, specifically designed for remanufacturing processes.

When questioned about the role of digital technologies in implementing the circular economy business model, the interviewee highlighted three key factors. First, concerning the market level, the adoption of an API integrated into the market. This API allows for easy ordering and delivery of products, resembling the purchase of brand-new items by customers. Without the API, the company would be unable to access the market already dominated by the original manufacturer's digitalized capacity.

At the company level, the second critical aspect was the development of an Enterprise Resource Planning (ERP) and Customer Relationship Management (CRM) system. This system facilitated component-level management of the 1200 individual components that comprised the project. From a purchasing perspective, the company can exercise control over their purchases. For instance, if the company purchases 0.5 million laptops in a year and there are 1500 different laptop types available, the company can limit the types of laptops that can be remanufactured. The interviewee also said that digital technologies like blockchain and digital passports could play a big part in solving this issue in the future.

Concerning the incorporation of Industry 4.0 in ELECTRO1, the interviewee clarified that while they have digitized their processes and utilize technologies like robot technology, cloud computing, big data, analytics and artificial intelligence, but they heavily rely on human expertise. The interviewee stated that they think digitalisation is only effective in a company when you have many people involved and are scaling up. Given that company

ELECTRO1 manufactures only a few remanufactured products compared to the number of laptops made by OEMs, it is not currently their top priority.

However, when questioned about the contribution of technology in achieving CE, the interviewee said that it provides immense value as evident below:

> *"Actually, I believe it's huge because incorporating more efficiencies in a circular economy would lead to quicker adaptation, particularly with smart technology and digitalisation, resulting in less room for error. This leads to fewer mistakes. Therefore, if you can increase quality and maximize efficiency, output and stakeholder value without reducing customer value, costs can be lowered. So, if you can simplify things and make them more manageable, is there a technology that can help us achieve that? I think there is, and I think it's currently being used by the linear economy. We need to take advantage of the linear economy's best practices."*

The interviewee expressed interest in technologies that bring value to customers and are reliable. Currently, there is some resistance towards AI due to a lack of trust in its capabilities as seen here:

> *"We just want what's best for the customer and we will use trustworthy technologies to achieve this goal. We strive to make the supply chain efficient from the point of entry to the next customer. Currently, I do not trust AI. If AI can be trusted, it would be beneficial only if it improves the customer journey and experience with us. Then, I am interested in achieving this because gaining customer loyalty is crucial. Believing in our mission is the key to achieving this. Therefore, if they believe in our mission and we satisfy their emotional needs, the intelligent agenda will follow."*

The most crucial factor is that customers have faith in the company's goals and that the company meets their emotional needs; then, intelligent solutions will naturally follow. The interviewee stated that, regrettably, technologies often reside in the realm of intelligence quotient rather than emotional intelligence.

4.1.2 Case study ELECTRO2

ELECTRO2 is one of Europe's largest non-profit IT companies, founded in Germany. Their business encompasses social, economic and environmental aspects. As a refurbisher of IT devices, they provide job opportunities for people with disabilities, who make up approximately 50% of their employees. Their products include cell phones, laptops, servers and printers, amongst other devices commonly used in a corporate setting.

The procedure entails the collection of used IT devices from business partners, followed by an assessment to determine their potential for reuse. In cases where the device cannot be reused, its components are shredded for further recycling processes. However, if the device is deemed reusable, its data is deleted, and the device is refurbished and repaired. The resulting product is then made available for purchase by private consumers through online shops.

Regarding the challenges encountered when implementing a circular business model, the interviewee identified their primary difficulty to be related to product design. This is due to the manufacturers' designs not considering the disassembly of products in the future, as outlined here:

> *"The main challenge we face is product design. If a product is not designed to be repaired and reused and contains glues and non-replaceable parts, it becomes highly inefficient and time-consuming to repair. Spending an hour to repair a device is acceptable, but spending a whole day is not. It is essential to design products that are efficient and practical for repair and reuse, while still remaining economically viable. The product manufacturer did not consider a circular economy approach during the product design phase, making it difficult for us to implement sustainable practices. However, the task is exceedingly arduous. This presents a significant challenge for our operations. Despite this obstacle, we continue to strive towards improving our processes and increasing our reuse rate."*

The primary capability that ELECTRO2 had to cultivate to implement their circular business model was knowledge. The company had to acquire the knowledge of examining the product, determining necessary measures, ensuring data safety, and managing lithium in batteries. These aspects had to be learned for ensuring a safe and informed process.

The circular model resulted in heightened awareness surrounding the circular economy, social inclusion, and diversity amongst business partners. As part of the model, business partners provide the company with their used devices, in exchange for sustainability reports and employee discounts, which contributes to increasing awareness on the topic.

In terms of the manufacturing process, the interviewed party clarified that although highly manual, the entire process is supported digitally by an ERP system. When a device is received by the company, it undergoes scanning and all data for the device is stored, thus enabling visibility of the product's location in the warehouse, its original customer, and the nature of the device, facilitating rebuying by business partners. ELECTRO2 aims to enhance its operational efficiency by increasing the refurbishment and reuse rate, as well as minimising the number of parts that undergo recycling. This involves conducting a comprehensive analysis of the entire process and exploring digitalisation to identify suitable technologies that can facilitate the desired improvements. However, they are not considering adopting I4.0 technologies as seen here:

> *"So, we are analysing the process in our house and to do that we are trying to improve the digitalisation, what can support the process, but it's not Industry 4.0 to be honest."*

Besides that, the interviewee reported that increasing automation in the process is not one of their priorities and automation is associated with a negative perspective of loss of job opportunities, as mentioned here:

> *"Our main goal is not 100% automation, as we aim to provide workplaces for people with disabilities."*

The company has limited adoption of I4.0 technologies due to the highly manual process. Apart from utilizing the ERP system, an external company provides them with data erasure software stored on their server. The software connects to the company's computers and the partner's devices, collecting statistical data and deleting information. Finally, regarding Smart Supply Chain technologies, ELECTRO2 has a system to share information with their business partners.

4.1.3 Case study ELECTRO3

ELECTRO3 is a small Brazilian enterprise providing reverse logistics solutions for electronic IT and ICT equipment disposal in accordance with the circular economy model. Their main product is refurbished laptops. The organisation comprises three key areas: environmental, economic, and social.

The environmental aspect involves collecting, inventorying, declassifying, certifying, valorising, and evaluating IT equipment for eventual recycling or refurbishment of the equipment. Additionally, the company provides every client with a socio-environmental impact report, outlining the environmental and social outcomes. Following reverse logistics procedures, IT equipment in good technical and operational condition undergoes a thorough quality and refurbishment process, resulting in products with a certificate of origin, traceability, quality assurance and technical support. Such devices are available for purchase at dedicated stores.

The social arm of the organisation is a non-profit entity that utilises resources obtained from equipment disposal and refurbished computer sales. The mission is to involve the private, public, and civil sectors in utilizing technological waste to enhance digital inclusion for underprivileged individuals, achievable through repurposing disposed devices into IT devices for use in socially beneficial projects supported by the institute, with ecologically sound considerations. Through this initiative, over 170 projects are benefitted, and more than 110,000 people are reached.

The company encountered two primary obstacles during their efforts to implement circular economy principles. The first issue to consider is the impact of the grey market on the electronics industry in Brazil. This market comprises all unauthorized distribution channels and is therefore unofficial. The defining feature of the grey market is the sale of authentic goods at significantly reduced prices, posing a substantial challenge for companies such as ELECTRO3, who cannot compete with the lower grey market prices. Additionally, the absence of legislation and certifications for the type of business conducted by ELECTRO3 presented another obstacle, because at the beginning the company did not possess any evidence of its quality and commitment processes. Today, the organisation holds a B Corporation certification and is undergoing an audit by ISO 14000.

When asked about the core capabilities necessary to implement their business, the interviewee explained that the entire process was novel in the Brazilian market and that they had gained knowledge and developed everything internally from scratch. Initially, they considered dismantling the devices and sending them to the United States or Europe for refurbishment and recycling because they were unsure about the processes within Brazil and did not believe that it was feasible to do it locally.

The interviewee was not familiar with the concept of Industry 4.0 technologies. However, following a clear definition of the term, the interviewee acknowledged several initiatives to ensure connectivity and traceability of the processes, enabling awareness of the entire process as mentioned here:

"I'm not familiar with the concept. To be honest, I've heard of it, but I've

never really looked into it. I don't think it's been fully adopted, because I don't really know about it. But as the company is in the process of constant growth, we haven't been able to keep up to date with this concept. But you've made some points about connectivity, and we have information about everything we do and we're turning it into traceability. We have a complete idea of what we do, how we do it, how far we do it. Maybe not completely, but I think we've adopted a good part, a large part of this industry concept."

Besides that, no automation initiatives have been implemented yet, as the process remains entirely manual. ELECTRO3 has adopted several base technologies such as cloud computing, big data and analytics. The company also designed the entire remanufacturing process to ensure traceability by developing its own database and ERP system. This was necessary as the existing linear market models had opposing logic and therefore were not a good fit. Currently, the company has an ERP system with its factory and another tool for managing commercial proposals and is working towards an integration of these two solutions. The aim of this integration is demonstrated in the following excerpt:

"We want to expand our ERP for our customers to see how I create a batch entry. We will also track items being processed, any ready for disposal, currently operational, and soon to be repaired or refurbished. At present, this information is not available in our system. The aim is to involve my client, as I can easily give them feedback and I can confirm that this material was mischaracterized."

ELECTRO3 is currently experiencing significant growth and facing numerous challenges; hence Industry 4.0 technologies are not currently their top priority. Nevertheless, they acknowledge its significance in the imminent future and are exploring potential technologies that could facilitate competitive advantages.

4.1.4 Case study ELECTRO4

ELECTRO4 forms part of a global automotive enterprise and is dedicated to the development of electric vehicles, specifically in the areas of drivetrain and battery systems for use in buses, industrial and commercial vehicles, ships, and rail vehicles. The company has a circular battery ecosystem, with a focus on developing strategies and partnerships for reuse, remanufacturing, and recycling.

Battery manufacturers utilise various design approaches depending on the specific application. Currently, there is a trend towards manufacturing systems that eliminate the need for individual modules. This is problematic as it reduces the chances of re-manufacturing and recycling. ELECTRO4 deviated from the prevailing design trend by adopting a modular design approach. One key indicator from their product is its ease of disassembly or repair, which aligns with circular strategies during the product's second life.

An obstacle faced by ELECTRO4 is the challenge of developing a re-use and re-design policy due to the extended life of its products, as the company doesn't know if a customer will return the battery systems as it is not mandatory. This challenge also makes assessing the technology difficult, as the uncertainty of obtaining enough used batteries in the future adds to the existing difficulties.

When discussing the core capabilities necessary for developing a circular economy, the interviewee suggested that having an individual who possesses knowledge of battery systems, regulatory issues, recycling technology, or business cases is crucial. This is important because a dedicated employee with sufficient time and knowledge can generate various ideas and options, which can be discussed with different partners for implementing them. The new business model for second life batteries brings two key benefits: an increase in clientele and improved customer satisfaction. The former will result from the introduction of second life services to new customers. The latter will be achieved through the product repair options, which extend product life and save customers money.

When asked about the role of digitalisation in transitioning towards a circular economy, the interviewee highlighted the availability of life cycle data through digitalisation as the key factor. This data can aid in determining the health of the system, providing a better understanding of what actions to take. This is particularly relevant for initiatives involving reuse and remanufacturing. The interviewee argued that combining AI, Computer Vision and other related technologies and testing could accelerate the development of circular products, given the abundance of datanecessary to implement circular strategies.

In relation to the implementation of Industry 4.0 technologies in ELECTRO4, the linear production line incorporates several tools such as KUKA robots. However, in the circular battery ecosystem, the adoption of technologies is still in the planning phase and is being investigated with the assistance of partner universities. They are planning to implement technologies such as computer vision, IoT, cloud computing, and analytics.

The main aim of utilising these technologies is to automate the evaluation of the system's condition or faults during the remanufacturing of a component, while also simplifying and automating the disassembly process.

Regarding achieving CE through technology, the respondent stated that it enables the evaluation of a product's suitability for end-of-life management. In cases where it is unsuitable, modifications can be made. The technologies aid in identifying general quality standards for determining any system-related issues and for categorising components as remanufacturable, reusable or for recycling purposes.

4.1.5 Case study ELECTRO5

ELECTRO5 is an ecosystem of circular economy in Brazil, comprised of three entities: a global manufacturing company that specialises in electronics manufacturing services, a sustainability and circular economy innovation centre devoted to reverse and recycling logistics operations, and a research institute engaged in the development of new technologies for the circular economy. The company has been recognised by the World Economic Forum in its Global Lighthouse Network, which acknowledges ELECTRO5 as a leading enterprise leveraging advanced Industry 4.0 technologies. The combination of Industry 4.0 with sustainability initiatives is crucial for competitiveness, resilience, and productivity in today's market. The success of ELECTRO5 can be attributed to its integration of people, technology, and the environment, which has resulted in the implementation of circular economy processes and solutions. These include remanufacture, reuse, repair, recycling, waste reduction, end-of-life equipment management, and reverse logistics.

One of ELECTRO5's most noteworthy initiatives is its comprehensive Zero Waste certification programme, which strives to facilitate the reintegration of nearly all waste generated within its facilities into the production chain. The following excerpt provides a detailed account of this initiative and its underlying rationale, as articulated by the interviewee:

> "*We started this project 12 years ago and the process to achieve zero waste took three steps. The first step is to ask yourself if it makes sense for us to throw garbage from the inside of the company to the outside, whether it is industrial garbage, waste, cardboard, plastic, etc. Does it make sense? It doesn't make sense and it is not the best solution. Sanitary landfills are a simple solution for our waste, but we've just got used to it. It doesn't make sense, though. I'd say the first step was to stop our waste leaving the company and going*

to the landfills. We've done that now, and the entire ecosystem is certified as zero waste by the United Nations. So, we stopped sending anything to the landfills. The second step was to look at the products we make, like phones, computers, printers and servers. At some point, they become electronic waste. Does it make sense to leave that in society? No, it doesn't. So, we created a reverse logistics system to bring it back to society, to the fabric environment, to recycle what we could, and to turn it into new products. This was also a step we achieved back then. The third step is to design products that generate less garbage, or ideally don't generate any at all in the future. That was the responsibility of the research institute. They developed methods and technologies on how to make the product, tips on how to make the packaging, use of different materials and so on."

Furthermore, ELECTRO5 has implemented a circular economy initiative focused on reverse logistics. This initiative leverages sophisticated logistical networks and partnerships to ensure the proper collection, transportation, and processing of electronic waste and other discarded materials. The objective is to minimize the environmental impact and maximize the recovery of resources. A robust infrastructure, including dedicated collection points and logistical routes, has been developed to facilitate the seamless retrieval of end-of-life products from various sources. These sources encompass discarded items from consumers, excess inventory from manufacturing processes, and returned goods from customers.

Through its proprietary reverse logistics system, ELECTRO5 collects items such as laptops, cell phones, computers, printers, cartridges, toners, and servers. Subsequently, these items are transformed into raw materials for the manufacture of new products, with approximately 96% of all received material being reused. Some materials are converted into plastic resin for the production of new electronic components, while others are recycled for other applications. Finally, a small proportion of materials is transformed into common-use products such as benches and pallets for industry. Rigorous laboratory tests are conducted to ensure that the quality of the recycled plastic is equivalent to that of virgin resins. Moreover, ELECTRO5 completes the productive cycle of plastic recovery by transforming plastic originating from electro-electronic equipment into raw material for new equipment.

Advanced sorting and processing techniques are employed by ELECTRO5 upon collection, effectively segregating different types of materials and components. This facilitates the efficient disassembly and separation of valuable resources, including metals, plastics, and electronic components, which can then be recycled or reused in new products. By maximising the recovery of these materials, ELECTRO5 minimises the necessity for the utilisation of virgin resources and reduces the environmental impact associated with traditional manufacturing. Furthermore, through remanufacturing, ELECTRO5 restores used products to like-new condition, extending their lifecycle and reducing the demand for new materials. Remanufactured products undergo rigorous quality control processes to ensure they meet or exceed industry standards.

The research centre, a cornerstone of ELECTRO5's operations, plays a pivotal role in the collection and processing of materials on a national scale. Equipped with physical points in various regions and logistical models tailored for large companies, the centre ensures the efficient recycling of post-consumer products. At the innovation centre, equipment such as printers, cell phones, and ink cartridges is meticulously disassembled, de-characterised, and sorted according to their properties. Plastic is crushed, melted, and granulated for use in injection machines to create new parts, while non-plastic materials are sent to partner recycling centres. Furthermore, ELECTRO5's integration of recycling discarded products with new product manufacturing marks it as the world's first plant of its kind. The company is fully prepared to receive recycled materials and parts, exemplifying a pioneering case of circular economy, significantly reducing costs and emissions resulting from transportation.

In terms of the challenges that ELECTRO5 faced when implementing a circular economy, the interviewee identified two main challenges. The first of these was a bureaucratic challenge, which arose when reverse logistics were established a decade ago. At that time, certain states in the country required a tax note for returning broken equipment. This meant that consumers who wished to dispose of electronics in an environmentally responsible manner were unexpectedly asked to provide documentation before their items could be accepted. While individuals may be required to provide a letter in certain instances, legal entities are obliged to produce a tax note, which adds complexity and cost to the process. This bureaucratic aspect presents a significant obstacle, particularly for multinational companies, which must navigate within strict legal frameworks and cannot operate in grey areas.

In addition to the bureaucratic challenges, there were significant technical hurdles to overcome in the transition to a circular economy. Unlike the linear economy, which has been refining processes and optimising machinery for centuries, circular economy practices are still in their infancy. While linear systems boast impressive machines for mineral extraction, equipment assembly, and material refinement, the circular economy lacks similarly efficient technologies for equipment disassembly and recycling. The closing of the aforementioned technological gap and the making of circular economy machinery just as productive as its linear counterpart are daunting tasks, requiring substantial innovation and investment.

Furthermore, these challenges, which include bureaucratic and technical difficulties, generate additional costs, as the high costs associated with recycling and reverse logistics stem from the lack of prepared bureaucracy for formal processes and the inefficiency of equipment. Additionally, cultural factors play a role in this regard, as proper disposal practices are not yet ingrained in society's mindset. Even those with a high level of education may find it challenging to identify appropriate disposal methods, underscoring the need for enhanced awareness and education about sustainability practices.

When questioned about the role of digitalisation in achieving CE, the interviewee acknowledged the potential of technology to streamline processes, reduce costs, and enhance efficiency. This is exemplified by the following:

> "*We have always embraced technology as a means of overcoming various challenges we face. One example is the logistical hurdles we encountered due to rising costs. In 2012, we developed a cloud-based collaborative system specifically tailored to tackle this issue. Leveraging our expertise in technology, we implemented this system, which resulted in a significant 30% reduction in logistics costs. This success led us to consistently seek technological solutions to enhance efficiency across our operations. What sets us apart, particularly at ELECTRO5, is the scale of our operations. We're not talking about small-scale pilots here; our operation processes over 200 tons per month, with a workforce of 90 to 100 individuals. This necessitates robust technological infrastructure spanning manufacturing and logistics systems. Logistics, in particular, exemplifies the transformative power of digitisation. Previously, our processes relied on cumbersome methods like Excel spreadsheets and email communications, leading to inefficiencies. However, by implementing a collaborative cloud-based system, we streamlined communication and decision-making processes among stakeholders, resulting in faster and more cost-effective solutions. Our commitment to digitalisation extends beyond logistics. From warehouse management to manufacturing systems, we have embraced technology at every level. This dedication has been acknowledged by the World Economic Forum, which has*

> *honoured ELECTRO5 as a Lighthouse of technology and sustainability. This underscores our comprehensive approach to digitisation. In essence, technology has been integral to our ability to address challenges and drive efficiency in our industry. By continuously seeking innovative technological solutions, we are not only overcoming obstacles but also paving the way for a more sustainable and resilient future."*

Regarding the adoption of base technologies by ELECTRO5, the respondent stated that the company has adopted all technologies. The factory is composed of an IoT-enabled digital performance management system connected to all 44 production lines, including the circular economy lines. This system provides real-time data and transparency, resulting in a reduction of material loss by 81% and an overall equipment effectiveness increase of 23%. Furthermore, the joint adoption of IoT and cloud technologies in their circular economy ecosystem has resulted in a significant positive environmental impact, with a 94% reduction in material waste and a 38% reduction in plastic material costs.

One illustrative example of the application of base technologies in reverse logistics is an innovative solution in the context of waste management, namely a smart rubbish bin. The emergence of this solution can be attributed to the challenges faced by Brazil in terms of the high logistical costs and pollution associated with transporting waste. As the country relies mainly on road transport, finding ways to reduce the costs and environmental footprint associated with this practice is crucial. By using IoT technology to optimise e-waste collection, the smart rubbish bin directly addresses these challenges. This device is equipped with sensors that continuously monitor how full the bin is. Upon reaching its maximum capacity, the bin automatically triggers a collection alert, notifying those responsible for emptying the container. This data-driven approach allows for more efficient waste management, reducing logistical costs and minimising pollutant emissions associated with the unnecessary transport of empty bins. Furthermore, the smart rubbish bin is produced with recycled materials and utilises sustainable manufacturing methods, exemplifying a holistic approach to dealing with the logistical and environmental challenges facing Brazil.

Other base technologies, such as big data and analytics, were also adopted to carry out life cycle analyses of their products, processes and business models. This was done in order to understand the associated environmental impacts and to simulate different scenarios with the aim of reducing this impact and increasing the circularity of their operations and products. Big data is utilised to handle data from 30,000 lifecycle datasets, while analytics is utilised to create charts and dashboards for decision-making purposes. These technologies are adopted together with computational modelling and simulation. Computational modelling enables the performance of a product's actual life cycle to be modelled, while simulation can support the emulation of different scenarios. These scenarios may include reducing dimensions, thicknesses, changing materials and incorporating recycled raw materials, as well as changing business models. The objective is to generate a positive social and environmental impact, and to assess the environmental performance of improvement proposals.

In terms of the adoption of smart manufacturing technologies, ELECTRO5 employs a range of digital technologies in the linear production line, including automation, virtualisation, vertical integration, flexibility, traceability and energy management. However, in the circular line, not all technologies are utilised, given that automation is only possible when a significant volume of identical products is available. Furthermore, the volume of products required for remanufacturing processes is not as high, and the quality of the items produced varies considerably. Consequently, in the circular line, ELECTRO5 could automate the stages of reception, the expedition, stock controls and inventory of second-hand products. However, the processes of repair, refurbishment and remanufacture are still somewhat manual due to the variability of the products' conditions. Additionally, the same quality assurance systems and methodologies from the linear lines are utilised in the circular lines, which assures high quality in its remanufactured and refurbished devices.

The circular lines make use of a variety of digital technologies, including flexibility, traceability and energy management technologies. With regard to flexibility technologies, ELECTRO5 employs 3D printing technology to fabricate manufacturing devices such as molds and templates that are designed to facilitate the assembly and disassembly processes, thereby ensuring facilitated repair and remanufacturing processes. Furthermore, ELECTRO5 makes use of a multitude of sensors to enable real-time data from their entire circular ecosystem, thus ensuring traceability and also energy management.

When questioned about the integration of smart working technologies in the circular production line, the interviewer highlighted the prevalence of visual management. Objectives are displayed on panels and digitally updated in real-time, facilitating performance tracking throughout the day. Additionally, the implementation of an award-winning health and safety system in Brazil is noteworthy. This system utilises digitised ergonomics and mathematical calculations based on medical standards to assess injury risks for operators. By modifying work instructions and workstation configurations as necessary, the probability of injuries can be diminished. Despite ELECTRO5's global resources, the emphasis remains on continuous improvement and innovation within the organisation.

In regard to the advancement of Smart Supply Chain technologies, the interviewee indicated that ELECTRO5 has not witnessed significant progress, not only within the company, but also across industries in general. While training is conducted within certain portals on supply chain management, effective implementation remains lacking in many companies, based on the interviewee's market knowledge. Pilot programs are in place, but they are often limited to a handful of suppliers and face significant challenges. For instance, while orders may be automatically generated, tracking the quality of the products from suppliers remains a manual process. While quantities and arrival times can be monitored, ensuring quality control at the supplier's end is not yet fully automated. This highlights a gap in the flow of materials where automation has yet to fully penetrate. As the company moves forward, the interviewee said that addressing these challenges will be crucial for enhancing overall supply chain efficiency and quality assurance.

When asked about potential technologies to be implemented in the future, the respondent stated that artificial intelligence emerges as a paramount candidate, already demonstrating utility in diagnostic procedures with expansive potential applications. In contrast, while blockchain technology garners considerable attention, its practical applications remain relatively constrained. The inherently intuitive nature of artificial intelligence suggests a trajectory towards widespread adoption, potentially facilitating advancements in robotics and automation, particularly within reverse cycles of production and logistics. The following extract illustrates the interviewee's perspective on the potential of digital technologies to enhance circularity.

> "*It is my firm conviction that technology represents the key to overcoming cost barriers, a pivotal factor in advancing sustainable practices. In pursuit of disruptive technologies, I recently proposed to a partner university the creation of a consumer-oriented system. This system would leverage cameras and apps to provide personalized recommendations for optimal device usage and disposal methods. By addressing individual needs and contexts, such technologies have the potential to mitigate the cost barriers that currently exist and to drive increased adoption rates. As volume increases, scalability and efficiency improvements follow, bolstered by enhanced competition and streamlined processes. Furthermore, material identification poses a significant challenge,*

> *particularly with plastics. To tackle this issue, we have explored advanced techniques such as artificial intelligence and hyperspectral imaging. Through ongoing research and innovation, we aim to overcome these challenges and pave the way for a brighter, more sustainable future.*"

4.1.6 Case study HOUSE1

HOUSE1 is a global producer of household appliances, specialising in white goods such as fridges, small appliances, washing machines, dishwashers, tumble dryers, vacuum cleaners, and microwaves. The business implements a sustainability strategy throughout their entire supply chain, with the goal of providing more environmentally friendly solutions, more efficient operations, and ultimately creating a healthier and more sustainable lifestyle. One of their key objectives of their sustainability framework is to offer circular products and business solutions.

According to the respondents' perceptions, the company's level of adoption of the circular economy falls between the planning and adopted stages. The excerpt below elucidates this classification:

> *"It's difficult to determine the actual level of adoption as it seems to be between the planning and adoption stages. In a qualitative way, a lot of things have been addressed and a lot of areas are covered. But how much progress have we made if we look at the numbers? I would say, not much progress. In a qualitative way, quite a few people are aware of the initiatives, but the company has a long way to go to be fully circular according to its own definitions."*

The first topic on their circular agenda is to integrate recycled materials in the products. As the growing demand for resources is attributed to the increase in global population, the company performed a carbon footprint analysis on their materials to determine how they could contribute towards a more sustainable production. It was found that steel had the greatest environmental impact, hence a partnership was formed with a supplier who utilises recycled steel made from scrap steel, renewable energy and carbon capture technologies to make a positive contribution.

Additionally, the study indicated that prioritising the integration of recycled plastics into their products was a key focus. Consequently, they set a target to raise the percentage of recycled plastics to 50% by 2030. HOUSE1 is collaborating with a partner to create a recyclability tool for designing all product categories that incorporate recyclability aspects and can easily be repaired. To reduce plastic waste and the demand for new materials, HOUSE1 has created a fridge with inner liners made of recycled plastic. This marks the first product on the market to use 70% recycled plastics in its liners, which accounts for 13% of the overall plastic used in the fridge. Additionally, the company is striving to encourage their OEM suppliers to incorporate more recycled plastics in their products.

Regarding their efforts to adopt circular business models, HOUSE1 has recently introduced a subscription service for home appliances. This service offers both new and refurbished appliances as options to aid people in living a more sustainable lifestyle. By subscribing, customers can choose their preferred appliance, select a suitable subscription plan, receive doorstep delivery within 48 hours, dispose of their old appliance for free, and access maintenance services for their new appliance. When an appliance malfunctions, HOUSE1 strives to repair it, thereby prolonging the life of your current appliance. By choosing to consciously repair your device instead of disposing of it once it breaks down beyond the manufacturer's warranty period, you contribute to reducing waste. If a product cannot be repaired within 14 days, it will be replaced with a new one and the old product is collected, and its parts are recycled or reused to reduce electronic waste and improve resource efficiency.

When asked about the challenges of applying circular strategies in their current linear model, the interviewee clarified that integrating recycled plastics into existing products demands a shift in working methods and entails some risk due to the inconsistency of the recycled material, causing resistance from the manufacturing department of the organisation. However, the purchasing department or the organisation is interested in purchasing recycled materials as they are more cost-effective than non-recycled materials. Another challenge identified was to develop a new business model or alter an existing one within the organisation. Conflicts of interest often arise in such circumstances, and thus it is essential to make a concerted effort to minimise any such conflicts to enable CE initiatives.

Regarding the fundamental capabilities necessary for applying CE strategies, the interviewee stated that the crucial aspect is to possess dedicated individuals within the company who strive to keep others informed and persuade them about the significance of the CE project through showcasing its potential advantages. The management must be persuaded that the initiatives can enhance customer satisfaction and boost sales figures.

When discussing the role of digitalisation in enabling circular economy, the interviewee asserted that it has not had a significant impact on the CE project and therefore has not been fundamentally important. However, the interviewee suggested that the CE project may have achieved more with a digital infrastructure in place as it would have enabled greater data collection as mentioned here:

> *"Digitalisation has not yet played a significant role in the CE project. However, it could have had a more significant impact if there were a digital structure in place. A recent project driven by the service organisation provided detailed information about customers' locations and needs. The project supported circular economy ambitions, but it was driven by other reasons, not fundamentally by circular economy ambitions."*

HOUSE1 has integrated several Industry 4.0 technologies, such as IoT, cloud computing, big data, ERP, AI, and robots, into their linear line. However, these technologies are yet to be adopted in the circular line. The interviewee acknowledged that these technologies are not new to the company and are progressively gaining significance, particularly as digitalisation is expected to trigger the next wave of operational efficiency. The company is currently making a collaborative effort to enhance device connectivity, particularly through IoT. This is being extended to include circular business models, as connectivity presents opportunities for improved resource efficiency. However, the interviewee acknowledged that it is difficult to demonstrate the benefits of connectivity to customers as described here:

> *"When we talk about connectivity and the Internet of Things, I think it's not easy to show the customer, the end user, the very strong benefits of connectivity. It's not obvious. Why should you or I as a customer buy a connected washing machine? What's the point? Maybe there are huge benefits, but in that case, I don't think the customer has been convinced of that, you can do it in different ways, but I think maybe there should be some kind of consensus to say that big benefits or not, the customer hasn't picked it up in that big way. If the customer doesn't see the benefit, what's the motivation to use it, right?"*

4.1.7 Case study HOUSE2

HOUSE2 is a multinational producer of household devices and one of the largest in Europe. Their portfolio includes 11 brands that address a range of consumer needs including cooking, dishwashing, washing and drying, refrigeration and freezing, consumer products, home connect, and connected home appliances.

The company´s sustainability strategy seeks to demonstrate to consumers, employees, and society at large that preserving the climate and environment are not inherent impediments to economic prosperity; in fact, these objectives complement one another and should be pursued together. In their perspective, implementing sustainable operating practices is crucial for companies to secure their long-term market viability, given that both customers and governments increasingly prioritize this approach. The sustainability programme strives to achieve circularity through initiatives in the circular economy, with a particular emphasis on the integration of measures promoting recyclability, durability and repairability.

Regarding the recyclability aspect, HOUSE2 aims to increase the proportion of materials that are recyclable in their products to at least 80% by 2023 and at least 95% by 2030. Additionally, the company intends to enhance the use of recycled materials in their production processes, with a goal of constructing products containing a minimum of 25% recycled materials by 2025. For 2030, the goal is to double this figure to at least 50%.

To achieve these objectives, the company has initiated several measures. Firstly, the company aims to reintroduce products into the material recovery process at the end of their usage period and reprocess them for further use, either partially or in their entirety. If this is not feasible, it is essential to guarantee that the items are subject to advanced recycling via mechanical and chemical procedures. At the design stage, they are ensuring the use of environmentally friendly materials and avoiding critical substances that could disrupt the recycling process or limit the use of recycled materials. Additionally, they are reviewing their jointing methods to prevent permanent attachment through adhesives or welding for components that require separation before automated recycling procedures commence. Click/snap-solutions could provide easy removal instead.

HOUSE2 has also introduced two new circular business solutions. The first project provides a product-service-system model that offers the opportunity to rent out home appliances at a fixed monthly fee, with HOUSE2 remaining the owner of the appliance. Repairs, replacements, and maintenance are included in the subscription, ensuring a hassle-free household. When appliances are returned to HOUSE2, 97% of them are refurbished by professionals at the company's maintenance centre. This helps to prolong the technical lifespan of the product and ensures their reuse by other households, ultimately reducing the manufacture of new products. The refurbished items are cleaned and checked after the subscription period, subsequently undergoing repair if any part is broken. When a device cannot be refurbished, the remaining 3% of appliances are recycled. Furthermore, the initiative gathers small electrical appliances from various other products and brands, which are subsequently recycled.

The second project is a sharing system for washing machines and dryers that aims to reduce the number of appliances required in the market. This initiative offers an innovative digital solution that includes booking and billing systems for communal laundry rooms. Digital technologies have played a significant role in modifying users' experience. To utilize the app, customers must register on a platform that enables them to check machine availability, make reservations and track when their wash cycle is completed. To employ this system, an IoT kit is inserted between the device and the power outlet, gathering all essential data in real-time. This kit may also be utilised in older appliances, as otherwise newer energy-efficient appliances are utilised.

When asked about the difficulties in implementing CE solutions, the participant cited outdated and not widely used standards as the main barrier, as shown here:

> *"Standardization is crucial for all manufacturers as we require a universal standard to enable comparison and to prevent greenwashing. If we consider current standards, such as the recyclability of products, we find that they are outdated and require review. Ensuring visible standardization is necessary for manufacturers, governments, and other organisations to achieve comparable situations."*

A necessary capability for implementing CE solutions has been an understanding of the different areas and issues that need improvement to reduce environmental impact. In relation to making products more durable by making them easier to repair, certain questions arise. These include what parts should be repairable, the key functions and components, and how to approach repair for each product type, as different requirements apply to televisions, cooktops and washing machines. HOUSE2 also had to learn how to select the appropriate materials for their products to ensure recycled products were widely available while still maintaining high quality. Moreover, incorporating recycled materials into the procedures requires adjusting the processes and tools, which may result in additional expenses.

When questioned regarding the role of digitalisation in achieving CE, the interviewee stated that digitalisation is a main driver for CE due to its ability to simplify and clarify many processes. It has the potential to provide transparency in information, such as the composition of appliances in terms of materials and parts, which can be useful for recycling and refurbishment. Furthermore, digitalisation can work as a key tool to propel further the topic of circularity and make it more visible.

Regarding the adoption of Industry 4.0 in HOUSE2, the interviewee reported limited knowledge of these technologies and noted that the company is in the early stages of implementation due to the highly manual nature of their processes. Nevertheless, the interviewee acknowledges that blockchain technology could be valuable in the future, as it has the potential to improve transparency and traceability.

4.1.8 Case study FURNI1

FURNI1 is a UK-based office furniture company that designs and manufactures a variety of office furniture, such as chairs, tables, sofas, and acoustic pods. The company is presently creating circular business models and solutions to maximize available resources while achieving the highest possible value for an extended lifetime, while also aiming to reduce waste whenever feasible. The interviewee stated that remanufacturing could be a powerful strategy to achieve this objective, as outlined here:

> *"Although improving the carbon footprint of new materials can achieve significant progress towards deep decarbonization over the next few decades, I don't believe achieving a genuine net zero position is possible by only reducing our carbon footprint by 90%. We must determine a way to separate turnover from the usage of new materials. This is where the circular economy and remanufacturing come into play as solutions. Remanufacturing is a lever we can use to significantly reduce our carbon footprint by reusing materials rather than constantly resorting to new ones. It allows for proper decoupling and a significant reduction in carbon emissions. This is why I'm passionate about remanufacturing. It enables us to decouple economic success from the use of new resources. Without incorporating remanufacturing, I don't believe we or any other product manufacturer could achieve a true net-zero reduction plan over time. It is imperative that we embrace remanufacturing as it aids us in achieving this goal."*

FURNI1 has recently launched a remanufacturing service which offers clients the chance to remanufacture their products, thereby prolonging product lifetimes and diminishing expenses and carbon emissions. The remanufactured products provide the same reliability and performance, but with a lower carbon footprint and at lower prices. Additionally, any replaced components are sent to a nearby recycling partner, ensuring nothing is sent to a landfill. This service is currently limited to a portion of their portfolio due to its recent implementation; however, they plan to extend it to other products in the near future.

The remanufacturing process comprises several stages. Initially, the customer specifies the furniture they intend to remanufacture, and outlines required repairs. Subsequently, FURNI1 quotes a price based on material, labour, and transport expenses. Following approval, the items are sent to FURNI1's facility, or service engineers perform the work on-site. After the work is complete, it undergoes a full audit and the customer is notified of the delivery date by email, if applicable. Upon delivery of the furniture, it is subjected to a scanning process, and the customer must confirm receipt, thus prompting the generation of a delivery note. Upon request, FURNI1 can provide a carbon savings report that details the amount of CO2 saved through remanufacturing rather than buying new items.

The enterprise has also taken the initiative to decarbonise their current and future product lines. That is why the products are designed to extract optimal design value from minimal resources for each product. The amount of recycled content has significantly increased, and the embodied carbon has been reduced, without any decrease in function or performance. Additionally, the products have been designed for easy disassembly and repair.

When asked about the challenges that FURNI1 encountered when deciding to transition towards a circular economy, the interviewee noted that the initial hurdle was finding the motivation to change. While climate change is an increasingly visible and tangible challenge, it may not always be enough to motivate companies to make paradigm-shifting changes to their operations across the board, unless there is a boardroom with committed and driven individuals who are committed to steering the company in the right direction. The interviewee emphasised the importance of the senior management team setting targets for remanufactured products, as these targets and key performance indicators help to measure the extent of circular strategies.

Furthermore, an obstacle faced in the market is that the available machines process materials in a single direction. Returning the product and attempting to reverse several processes, such as disassembly instead of assembly, pose significant challenges as they require the creation of numerous procedures that are currently non-existent. That is why they had to put in place some new procedures from scratch.

In relation to the implementation of I4.0 technologies in FURNI1, the interviewee indicated that they are in the initial stages of implementation as their assembly processes do not rely heavily on technology as stated here:

> *"We're still in the very early stages. I think it very much depends on what you classify as Industry 4.0. Because we don't use a huge amount of technology in our assembly process. You know, we're not as sophisticated as the automotive industry, which uses sort of digital tools to help people assemble car engines and things like that. We're quite unsophisticated and we're not really adopting a lot of Industry 4.0 technologies yet. I think we are quite traditional, we´re just using digital tools to help us capture and process information."*

Concerning base technologies, FURNI1 employs cloud computing for the majority of their daily operations, transferring their MRP (Material Requirement Planning), manufacturing system, and order processing system to cloud-based servers rather than physical ones. However, big data and analytics have not yet been implemented, and the respondent indicated that IoT integration is not a major focus. FURNI1 is composed of two production lines that have IoT capabilities and have the potential to deliver the benefits of IoT, but these capabilities are not currently being effectively utilised. Additionally, 3D CAD simulation is utilised in all product design for stress and displacement analysis to ensure accurate fit and function. This is crucial as they aim to maximise design value with minimal physical materials and require simulations for assessing the product's resilience and stability prior to physical production.

In the context of office furniture, the respondent stated that I4.0 technologies can play a vital role in asset tracking towards attaining CE. FURNI1 customers are typically large corporate entities with numerous buildings and diverse furniture holdings. Keeping track of furniture location and composition can significantly facilitate circular economy implementations. To enable the reuse of materials, it is crucial to have information about their location and composition. Revit files, which are basically BIM files, are available for nearly all items of furniture that are sold and provide comprehensive data on the products' composition, including the proportion of wood, metal, and plastic used and the fabric that covers the furniture. This technology, which they are currently integrating into their work, is highly advantageous for digital asset tracking.

Regarding the company's upcoming technology implementations, the respondent noted that FURNI1 prioritizes tracking technologies to improve product visibility. This may include RFID tagging or other low-cost innovations. At present, all products feature informative labels enabling clear product identification. However, this information is not stored within the product but only in the company records. Therefore, the enterprise is currently seeking ways to store this information directly on the product so that customers can easily access it without relying on our sales records to determine the product and its materials.

4.1.9 Case study FURNI2

FURNI2 is a rapidly expanding European sleep innovation business that creates mattresses, beds, toppers, and pillows and outsources their production. Whilst a relatively new company, FURNI2 is committed to prolonging product lifetimes and minimising environmental impact, leading to the launch of their second lifeline. This initiative remains limited in some markets and solely applies to the mattress line.

FURNI2's reputation is built on their firm promise to offer a 100-night sleep trial. A customer is entitled to return a FURNI2 product within one hundred days if dissatisfied. However, as returned mattresses come into direct skin contact and are difficult to assess, FURNI2 cannot simply re-sell them and must implement a refurbishment process to ensure the level of quality meets their standards. That is why they need to refurbish it to be able to resell it. The refurbishment process comprises thorough cleaning and sanitation of the product, replacement of the cover, and decontamination of the foam using UV light. Once the process is finished, the mattress is labelled as refurbished and sold at a discounted price. By reselling lightly used mattresses that are returned, the company avoids generating waste and ensures that the returned items have the lowest possible environmental impact. Moreover, this programme yielded financial benefits for the company as it enabled the sale of previously returned products that caused financial losses and thus minimized those losses.

The company employs additional circular economy strategies. The first initiative adopts the reduce strategy by introducing a new line of mattresses that consume fewer materials and have a lower environmental impact. Another initiative embraces the repurpose strategy, allowing to produce one product from another. An illustration of this scenario is when the company receives a mattress in poor condition, but certain parts are in satisfactory condition to make a pillow using the foam segment that is in good condition. FURNI2 also collaborates with numerous partners, who are accountable for recycling their products.

When questioned about the challenges encountered in implementing the CE plan, the interviewee responded that the primary obstacle lies in locating partners who serve as refurbisher and logistic collaborators for second-life products. The obstacle in locating refurbisher partners originates from the limited number of original product manufacturers willing to accept returns for refurbishment. Furthermore, the challenge in finding logistics partners willing to provide transportation services stems from three primary reasons. The initial factor is that a returned mattress takes up more volume than a brand new one, as the used product is not compressed during packaging and requires extensive effort for transportation. The second reason is that, due to the lack of packaging and the material composition of the product, it may become dirty, requiring additional effort from the logistics partner to ensure cleanliness. Furthermore, the process of product returns is highly individualized, and the need for refurbishment services is unstable and unpredictable, which presents further challenges.

Another obstacle the company faces is the deprioritisation of CE initiatives, due to the relative newness of the company and its current focus on running the business. The percentage of returned products is much lower than for new products, and the company also finds it difficult to prove to senior management that refurbishment is financially and operationally feasible. However, the interviewee stated that once FURNI2 achieves stability, managing returned products will likely become a key priority.

With respect to FURNI2's implementation of Industry 4.0 technologies, the interviewee reported that the refurbishment process remains highly manual and entails subjective decision-making regarding whether a mattress can be reused. Few technologies are currently involved in this process. To design products, FURNI2 relies on 3D CAD simulations and employs cloud computing, big data, and analytics for forecasting and uncertainty reduction. Additionally, the company utilises an ERP system which enables end-to-end integration from procurement to stock management, and this system is connected with their suppliers. The respondent asserted that adopting advanced technology could greatly enhance logistics automation, as indicated here:

> *"The logistics process is very manual. Today the box arrives at the warehouse, and we have to pick that box up, see who sent it to confirm a return and then check the product. Implementing technologies like RFID or bar codes would simplify the identification of returned products, enabling automatic integration to refund the customer. And also, this would be beneficial in a factory environment to separate the products more quickly, where we could differentiate if the product is packaged perfectly, has never been opened, and can now go straight back into stock. Today, we separate the boxes manually one at a time, and our partner charges us per box. Therefore, they must take each box from the truck*

and examine it individually. But if we had RFIDs that we could automate and thus improve the process's efficiency."

The interviewee also suggested that automating the quality assessment in the refurbishment process would be beneficial in the future as stated here:

"A machine could scan the mattress to detect mold, sunken springs, and other defects. This would enhance the overall process. This would be of interest because it would eliminate the need for an employee to carry out manual tests to ascertain whether a product should be refurbished or not."

4.1.10 Case study PILOT

PILOT is a learning, research, and development facility affiliated with a German business school. The factory serves as an exemplar of a smart manufacturing company, encompassing the entire industrial value chain alongside a dynamic product and service range. Specifically, it replicates and analyses processes regarding product and work system engineering, goods receipt, storage, picking, assembly and additive manufacturing. At PILOT the demands and impacts Industry 4.0/Industry 5.0 are researched in a practical manner through teaching and training programmes. The factory has a digital twin linked to the actual factory using communication and information technologies. This makes virtual planning and simulation of products and production, digital production control, and real-time monitoring of orders, workpieces, and resources possible.

PILOT has multiple initiatives that aid small and medium-sized enterprises (SMEs) in their digital transformation. One of these projects is specifically related to the circular economy in the car industry and it aims to build a decision support system for circular products, a computerised programme that assesses a company's circular strategies. It analyses and compiles a large amount of data and generates comprehensive information that could be used to advise the company on which sustainable strategy to adopt and which decision is better suited to solve its problems.

The teaching aspect of the learning factor is a key focus. Once university students have gained theoretical knowledge, they can apply it practically in the learning factory. PILOT offers two primary products, namely a scooter and a mobile working hub, and incorporates technologies to emulate diverse circular economy strategies. Currently, it is possible to simulate product use and manufacturing strategies, such as refuse, rethink, and reuse, that are more intelligent. Additionally, product lifespan can be extended through strategies that involve reuse, repair, refurbishment, remanufacturing, and repurposing. At present, PILOT lacks the capability to undertake recycling and recovery. However, their plan is to procure the necessary machinery to recycle PLA (Polylactic acid) plastics and incorporate these materials in 3D printing. The products have been devised in a modular fashion, enabling easy repair, disassembly and personalisation to the customer's preferences. Furthermore, biological materials are used in production, ensuring that, if necessary, they can be easily decomposed.

All these circular strategies are aided by a range of Industry 4.0 technologies which serve four primary objectives. The primary objective is to enable adaptability of the production line to changing requirements, which has been accomplished through the implementation of 3D printing, automated guided vehicles (AGV) and swarm intelligence (SI), an AI methodology that mimics natural behaviour to solve optimization problems through the collective intelligence of elements in decentralized and self-organised systems. The second objective is to enhance traceability and connectivity, which have been achieved through the utilization of RFID sensors, IoT, and blockchain technology. Automation is also an objective, and technologies such as collaborative robots, automated picking systems, and AGV are employed to attain it. Finally, through the use of virtual process simulation, artificial intelligence and virtual and augmented reality the ultimate goal is to promote virtualisation.

The discussed smart manufacturing technologies rely on IoT, cloud computing, big data, and analytics as supporting base technologies. PILOT also utilises smart supply chain technologies, facilitating supplier connections with the production line through a network in which various stakeholders can view and connect with ongoing activities.

Regarding the role of Industry 4.0 in attaining CE, the interviewee responded that I4.0 acts as an enabling factor by helping optimization and planning goals as stated here:

> "*I think the role of I4.0 in attaining CE is an enabling role. Of course, a company can practice circular economy through manufacturing without I4.0. However, the crucial question is how profitable and sustainable it can be for the company in the long run. So, I believe that all the technologies I mentioned are vital for designing circular business models. They enable the sharing of information among partners, making collaboration easier and more effective. You can say: 'We need this exact quantity of these parts now. Don't give us more because then we have to surge it or you have, we will lose resources.' The technologies can also have a positive effect in tracking parts and analysing what*

> *is being done in the factory and optimising it. You can also use technology to extract data from customer behaviour and understand which parts are going to break down more quickly, and that can help you design a better product.*"

When questioned about the technologies that PILOT intends to implement in the future, the interviewee stated that they plan to incorporate a shredder, which will allow for the creation of new materials made from old plastic components and a machine capable of processing metals. Additionally, they plan to introduce Schlauer Klaus, a comprehensive digital worker assistance system for inspecting incoming goods, automated optical identification, quality assurance, guided manual assembly and final optical inspection. PILOT aims to integrate additional sensors from various technologies and increase the number of servers to store more data in their factory.

4.2 Cross-case analysis

This section compares the case studies in order to structure the data collected and discuss the main similarities and differences between them. The primary circular economy approaches implemented by manufacturing firms, the struggles encountered in implementing these concepts, and the key technologies adopted by the surveyed organisations have been recognized and will be outlined below.

4.2.1 Circular strategies adoption

The purpose of this section is to examine the implementation of the R3-R6 strategies from the 9R framework presented in Chapter 2, as well as to determine which other strategies have been utilized in the case studies.

4.2.1.1 9R strategies adoption

The literature proposes an ideal hierarchy to follow among the 9R strategies to achieve CE. In the hierarchy, the strategies concerning smarter product use and manufacture (R0-R2) are considered the most valuable practices, followed by extend lifespan of product strategies (R3-R7) and then useful application of materials strategies (R8-R9) (KIRCHHERR; REIKE; HEKKERT, 2017). The featured organisations slightly follow this hierarchy, since all organisations have implemented strategies related to the extension of product lifespan, while only a few have adopted smarter product design and manufacture, and the useful application of materials strategies, as demonstrated in Table 5.

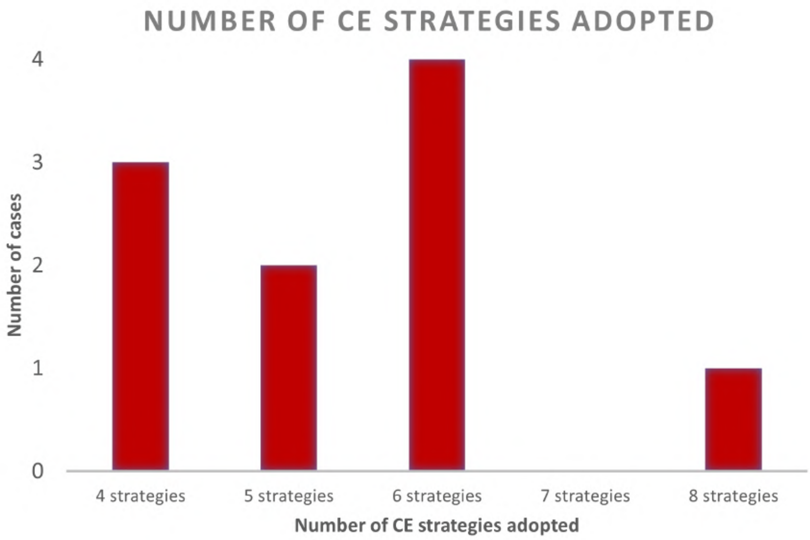
Table 5: Overview of 9R CE strategies adoption.

CE Strategy	ELECTRO1	ELECTRO2	ELECTRO3	ELECTRO4	ELECTRO5	HOUSE1	HOUSE2	FURNI1	FURNI2	PILOT	Number of cases	Case studies adoption rate
Refuse (R0)	X									X	2	20%
Rethink (R1)	X			X						X	3	30%
Reduce (R2)			X			X	X	X	X	X	6	60%
Reuse (R3)	X	X		X	X	X		X	X	X	8	80%
Repair (R4)	X	X	X	X	X	X	X	X	X	X	10	100%
Refurbish (R5)	X	X	X		X	X	X	X	X	X	9	90%
Remanufacture (R6)	X		X	X	X			X	X	X	7	70%
Repurpose (R7)					X				X	X	3	30%
Recycle (R8)		X		X	X	X	X		X		5	50%
Recover (R9)											0	0%
Sharing systems (PSS)						X					1	10%
Number of VRPs (R3-R6)	4	3	3	3	4	3	2	4	3	4		
Total number of CE strategies	6	4	4	5	6	6	4	5	6	8		
Adoption rate VRPs	100%	75%	75%	75%	100%	75%	50%	100%	75%	100%		
Adoption rate CE strategies	60%	40%	40%	50%	60%	60%	40%	50%	60%	80%		

Source: Created by the author

Furthermore, as illustrated in Figure 14, companies implementing circular business models typically employ a range of CE strategies rather than concentrating on a single approach. The average number of CE strategies adopted was 5.5, with a variability between 4 to 8 strategies. This suggests that businesses usually implement multiple approaches concurrently.

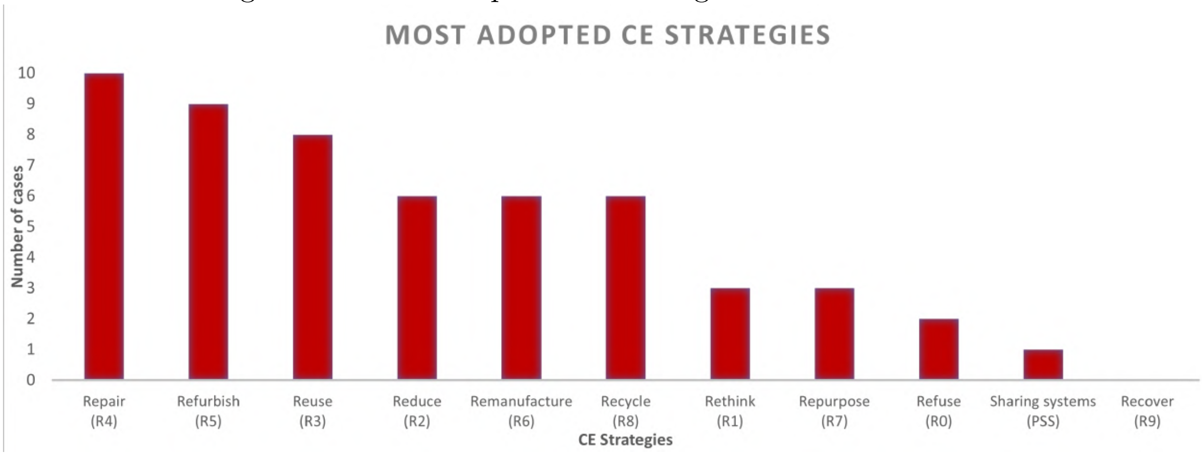
Figure 14: Number of CE strategies adopted by the case studies



Source: Created by the author

Of the various strategies investigated, repair (R4) was employed in all of the case studies, followed by refurbish (R5) in 9 case studies, reuse (R3) in 8 cases, reduce (R2), remanufacture (R6) and recycle (R8) in 6 case studies each as seen in Figure 15. This shows that the chosen sample has a distinct emphasis on strategies for VRPs, fulfilling one of the requirements of this study. As evidenced in the literature, the sample deviates from the prevailing trend in the majority of CE initiatives. This is due to the fact that most CE initiatives still disproportionately prioritise recycling over VRP strategies. By failing to prioritize or emphasize upstream waste reduction strategies, the majority of initiatives in the current production system remain fixated on incremental resource use optimization strategies, rather than addressing the continued use of resources as a whole.

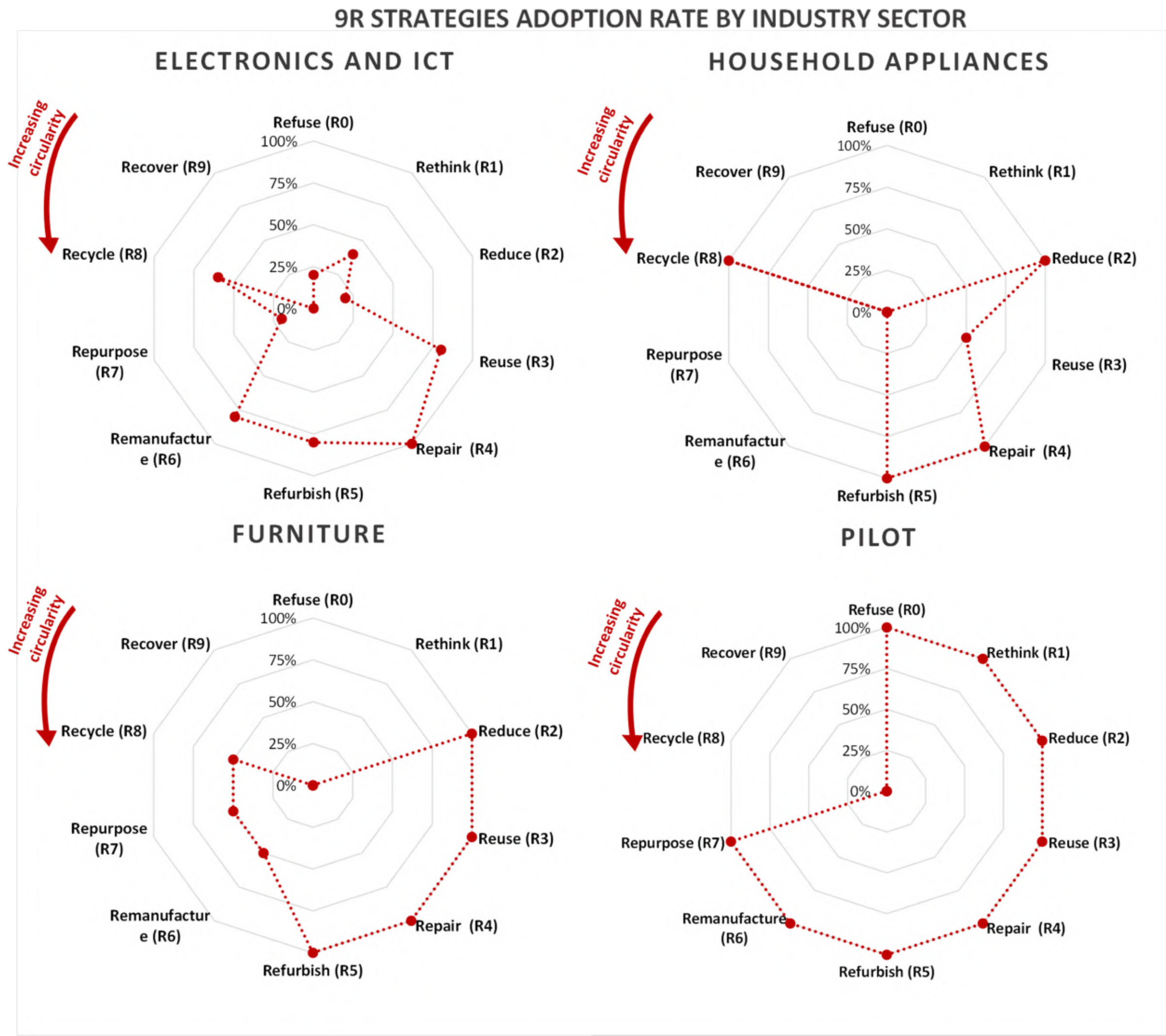
Figure 15: Most adopted CE strategies in the case studies



Source: Created by the author

When comparing the adoption rates of the 9R Framework for the four case study groups - electronics, household appliances, furniture and pilot - in Figure 16, it is evident that the pilot case achieved the highest circularity level. The furniture sector attained the second-highest level of circularity, with the electronics and ICT sectors following. Finally, the sector with the lowest level of circularity was the household appliances group.

Figure 16: 9R strategies adoption rate by industry sector

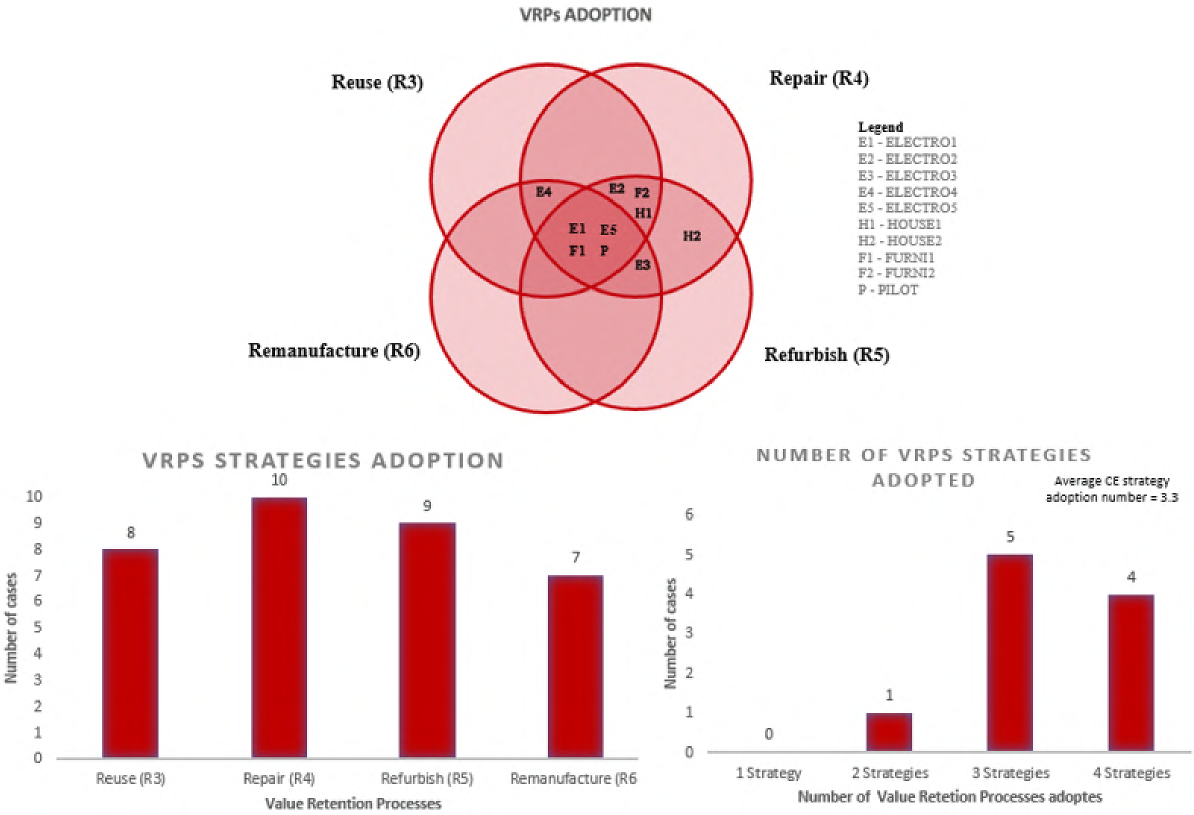


Source: Created by the author

4.2.1.2 VRPs adoption

Regarding the adoption of VRPs by the companies in the sample, Figure 17 shows that the most adopted strategy was repair, followed by refurbish, reuse, and remanufacture. The average adoption rate of these strategies is 3.3, suggesting that manufacturing companies are adopting multiple VRPs together, perceiving them as viable substitutes for traditional manufacturing and consumption methods and strategies to mitigate material scarcity concerns and extend product life.

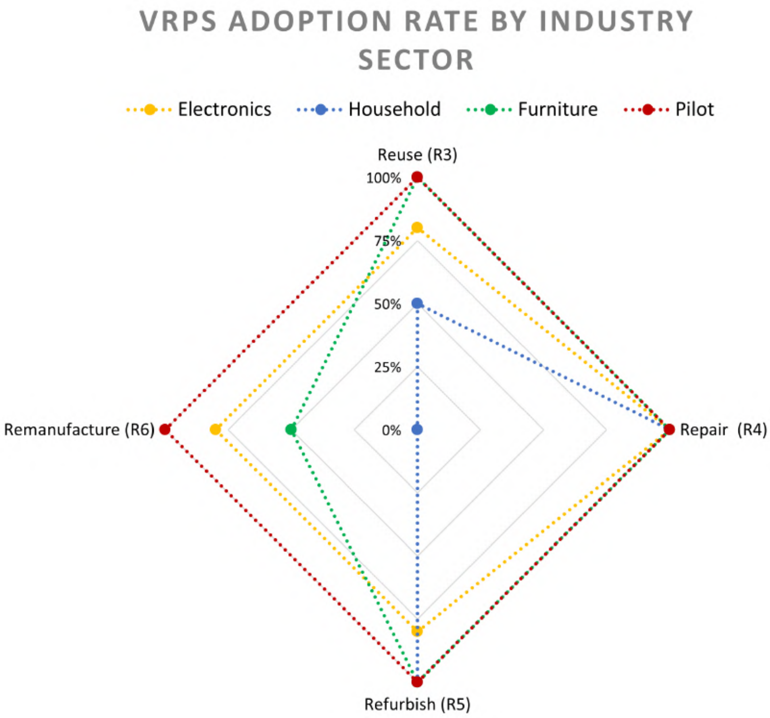
Figure 17: VRPs adoption in the case studies



Source: Created by the author

When analysing the adoption rates of VRPs in different industry sectors, it was observed that the strategy of reuse was more commonly adopted in the pilot case and the furniture sector compared to the electronics industry as observed in Figure 17. Additionally, the household sector exhibited less adoption of reuse than any other industry. Apart from this, there was no differentiation between the industry segments with regards to the implementation of the repair concept. The refurbishment strategy was fully adopted by all study groups, except for the household appliances group. Finally, the concept of remanufacturing was increasingly implemented in the following order of case study groups: furniture, electronics, and pilot cases. However, it was not adopted in any household appliance cases. Similarly, to the 9R strategy implementation, the pilot case achieved the highest level of circularity, followed by the furniture, electronics, and household appliances group.

Figure 18: VRPs adoption rate by industry sector



Source: Created by the author

4.2.1.3 Challenges in circular economy implementation

This section is dedicated to understanding what were the main challenges faced by the organisations in implementing circular economy strategies, using the challenges identified in Bressanelli, Perona e Saccani (2019). The challenges were grouped into eight categories: product characteristics and process challenges, standards and regulations, supply chain management standards, technology, economic viability, user behaviour challenges, organisational resistance and market and competition. Table 6 and Table 7 show the main obstacles identified in the case studies. PILOT case was excluded from this analysis because, as a university rather than a company, it does not make sense to analyse it together with the other case studies.

The category with the most occurring challenges was related to product characteristics and processes as seen in Table 6. The challenge of "lack of knowledge expertise" was reported in all case studies, as initially there were not many professionals with circular economy knowledge in the organisation. Research and training were required to overcome this obstacle. Six enterprises reported difficulties related to product complexity because new procedures and tools are required to implement CE strategies. The abundance of different devices may present an additional challenge to product complexity for refurbishers and remanufacturers. ELECTRO1, ELECTRO2, and ELECTRO3 also reported this difficulty. ELECTRO1 and ELECTRO2 also reported that OEM product design was a major challenge. The original equipment manufacturer usually does not consider repair and reuse during the design phase and uses non-replaceable parts in the product. This makes the disassembly process difficult for circular business models.

The second most cited group of challenges in the sample study was issues related to standards and regulations. All organisations cited the lack of standards in processes, materials, and activities as a challenge to implementing a circular economy. Some companies have reported that the lack of indicators and metrics around the context of CE is a challenge. Existing indicators were built around a linear economy perspective, aiming to maximize throughput and sales. However, CE requires a shift away from a purely volume-driven economic perspective to a more comprehensive one that encompasses economic, environmental, and social dimensions. One difficulty encountered was the strong political influence of OEMs, which may hinder progress towards a more circular economy. One case study reported that the absence of taxation, incentive policies, and legislation around their business type imposed additional difficulties for the company. As a small company, they did not possess any evidence of their quality and commitment processes.

The companies faced challenges with supply chain management standards, particularly with regards to return flows. Adopting circular business models can lead to uncertainty around the quantity, mix, quality, time, and place of returns, which can decrease the probability of achieving an economic scale and hinder capacity planning. According to ELECTRO4, a major challenge is the uncertainty surrounding the number of returned products, as it also affects technology assessment. Transportation and infrastructure can also pose additional challenges for companies implementing CE initiatives, especially for remanufacturers and refurbishers, as these companies may have higher transportation activities due to the reverse logistics flow. In addition, the availability of suitable supply chain partners may also be an obstacle. The FURNI2 case study demonstrated that reverse logistics processes can be particularly challenging for circular economy initiatives due to a limited number of transportation partners willing to offer this service. Additionally, the uncertainty of returned goods flows increases the complexity of logistics processes. The furniture sector is also highly affected by this barrier, as it deals with large goods that are usually difficult and expensive to transport.

Table 6: Challenges faced in the CE implementation by case studies - Part 1.

Category	Challenge	Description	ELECTRO1	ELECTRO2	ELECTRO3	ELECTRO4	ELECTRO5	HOUSE1	HOUSE2	FURNI1	FURNI2	Number of cases affected	Impact rate of each challenge
Product characteristics and processes challenges	Lack of knowledge expertise	Companies implementing circular economy approaches may encounter challenges related to a lack of expertise, as current professionals may not yet possess the necessary knowledge of circular practices.	X	X	X	X	X	X	X	X	X	9	100%
	Product complexity	Companies adopting CE approaches may face challenges due to novelty of materials that are used in circular designs, because they will require new procedures and tools. The abundance of different devices may present challenges for remanufacturers and refurbishers alike, as each device has its own unique set of specifications.	X	X	X			X	X		X	6	67%
	OEM product design	Companies adopting CE approaches may encounter challenges in disassembling their products. These difficulties arise from the original equipment manufacturer's failure to consider repair and reuse during the design phase, as well as the use of non-replaceable parts in the product.	X	X								2	22%
Standards and regulations	Lack of standards	Companies adopting CE approaches may face problems related to lack of standards in processes, materials and activities.	X	X	X	X	X	X	X	X	X	9	100%
	Measures, metrics, indicators	Companies adopting CE approaches may encounter challenges with regard to indicators. This is because existing indicators were developed around the concept of a linear economy, with the aim of maximising throughput. Circular economy requires a shift away from a purely volume-driven economic perspective to a more comprehensive one, encompassing economic, environmental and social dimensions.		X	X					X		3	33%
	OEM control	Companies adopting CE approaches can face challenges because original equipment manufacturers have a strong influence on policy and legislation, which can make CE adoption difficult.	X	X					X			3	33%
	Taxation and incentives	Companies adopting CE approaches may face difficulties in taxation systems, since the existing taxation policies, incentives and systems are aligned with the traditional or linear model and do not take into account the adoption of CE.			X							1	11%
Supply chain management standards	Return flows uncertainty	Companies adopting CE approaches may encounter challenges regarding the uncertainty of the quantity, mix, quality, timing, and location of returns for end-of-use products. This uncertainty can decrease the likelihood of achieving economic scale and result in complications with capacity planning.		X	X	X					X	4	44%
	Transportation and Infrastructure	Companies adopting CE approaches may face higher transportation activities and costs if they need to send all of their products back to producers or to firms that perform refurbishing and remanufacturing.			X					X	X	3	33%
	Availability of suitable supply chain partners	Companies adopting CE approaches usually experience difficulty in finding approapriate supply chain partners with appropriate skills.		X	X						X	3	33%
		Total challenge amount	5	8	8	3	2	3	4	4	6		
		Rate of challenges affecting each case study	50%	80%	80%	30%	20%	30%	40%	40%	60%		

Source: Created by the author

Table 7 presents the challenges identified in the sample of case studies. The subsequent category encompasses challenges associated with technological obstacles. This category was particularly prevalent in the electronics and ICT sector, as this industry is significantly impacted by constant technological advancements. The initial challenge pertains to issues with product technology improvement, as products designed for long-term use may not be able to participate in continuous technology improvement processes. The ELECTRO1 case highlights that some technology updates made by tech giants may not be compatible with older devices. This can create significant challenges for remanufacturing and refurbishing companies, as these older devices will not be able to access the latest technologies. Data privacy and security pose a significant challenge for the electronic industry. Many users are hesitant to return their used devices due to concerns about the retrieval and misuse of personal data. Therefore, companies that handle end-of-use devices may need to implement specific data-clearing activities to ensure data protection. ELECTRO2 reported a difficulty and developed a data erasure software in partnership with another company. The software collects statistical data and deletes information by connecting to the company's computers and the partner's devices.

The next challenge was to convince top management that adopting CE can be economically viable and provide a competitive advantage in the future. The novelty of the concept can be perceived as a high financial risk for the management team. This was specifically reported in the case studies of household appliances. The two organisations are large linear manufacturing companies and faced challenges in convincing top management about the feasibility and economic viability of CE initiatives.

The following section outlines challenges related to user behaviour. The initial challenge identified is to alter customer behaviour patterns, as they heavily rely on a linear perspective. Companies adopting CE initiatives may need to implement educational campaigns to promote a circular approach to consumption. Some customers may decline to purchase second-hand products due to status or fashion design reasons, or because they perceive them as less reliable or second-rate. This statement is already clear, concise, and objective. No changes are necessary. The ELECTRO 1 case study emphasised the significance of educational initiatives in raising awareness about circular products and changing the perception that remanufactured devices have lower performance than new ones.

The prevalence of linear mindsets and structures in industries can create limited awareness and commitment from both top management and employees, posing a challenge to CE initiatives. Additionally, unauthorized distribution channels can present market and competition issues. This may occur because grey markets offer significantly lower prices, which presents a substantial challenge to the implementation of CE approaches by companies like ELECTRO3 that are unable to compete with lower grey market prices.

Table 7: Challenges faced in the CE implementation by case studies - Part 2.

Category	Challenge	Description	ELECTRO1	ELECTRO2	ELECTRO3	ELECTRO4	ELECTRO5	HOUSE1	HOUSE2	FURNI1	FURNI2	Number of cases affected	Impact rate of each challenge
Technology	Product technology improvement	Companies adopting CE approaches may face challenges because products designed for long life would not be able to participate in continuous technology improvement processes.	**X**	**X**								**2**	**22%**
	Data privacy and security	Companies adopting CE approaches may have heightened concerns about data security and privacy issues when a device has previously been used by someone else. To address this, appropriate data-clear activities should be developed.	**X**	**X**	**X**							**3**	**33%**
Economic viability	Financial risk	Companies adopting CE approaches may face challenges in demonstrating to top management that CE adoption can be economically viable and lead to competitive advantage in the future, as the degree of novelty can be seen as a high financial risk for the top management team.				**X**		**X**	**X**		**X**	**4**	**44%**
Users behaviour challenges	Customer behavior change	Companies adopting CE approaches may encounter challenges due to current customer behaviour patterns that heavily rely on a linear perspective. It is necessary to address this issue by implementing strategies that promote a circular approach to consumption. Promoting sustainable consumption patterns and CE-centered consumer behaviour is crucial for implementing the concept of CE in practice.	**X**		**X**		**X**					**3**	**33%**
	User´s willingness to buy	Companies adopting CE approaches may face challenges because some customers may decline to purchase second-hand products due to status or fashion design reasons, or because they perceive them as less reliable or second-rate. This decreases the market size for refurbished and remanufactured products in comparison to brand new ones.	**X**		**X**							**2**	**22%**
Organization resistance	Cultural issues (linear mind-set)	Companies adopting CE approaches may face challenges because of internal resistance to change, particularly as prevailing linear mind-sets and structures in industries persist, which creates limited awareness and commitment from both top management and employees.						**X**		**X**	**X**	**3**	**33%**
Market and competition	Unauthorized distribution channels	Companies that adopt Circular Economy (CE) approaches may encounter obstacles due to unauthorised distribution channels. This may occur because such markets offer significantly lower prices, which presents a substantial challenge to the implementation of CE approaches by companies that are unable to compete with lower grey market prices.			**X**							**1**	**11%**
		Total challenge amount	4	2	4	1	1	2	1	1	2		
		Rate of challenges affecting each case study	57%	29%	57%	14%	14%	29%	14%	14%	29%		

Source: Created by the author

4.2.2 Enabling technologies adoption

This section aims to present which and how Industry 4.0 technologies have been used to achieve circularity, as well as the barriers organisations face in implementing I4.0.

4.2.2.1 Base technologies

The literature proposes that base technologies can support the implementation of front-end technologies, particularly Smart Manufacturing technologies. Therefore, it is crucial to analyse whether these technologies were utilized in the case studies. Table 8 shows the base technologies adopted by each organisation in the circular economy context. If a base technology was utilised in a linear economy, it shall not be included in the table.

Frank, Dalenogare e Ayala (2019) suggests a rising complexity level of implementing foundational technologies in the following order: cloud computing, IoT, big data and analytics. The sample analysed slightly followed this pattern since the most implemented technologies were cloud computing and analytics, with six organisations adopting them, followed by big data, with five organisations adopting it. On the other hand, the technology that was least adopted was IoT, with only three case studies implementing it.

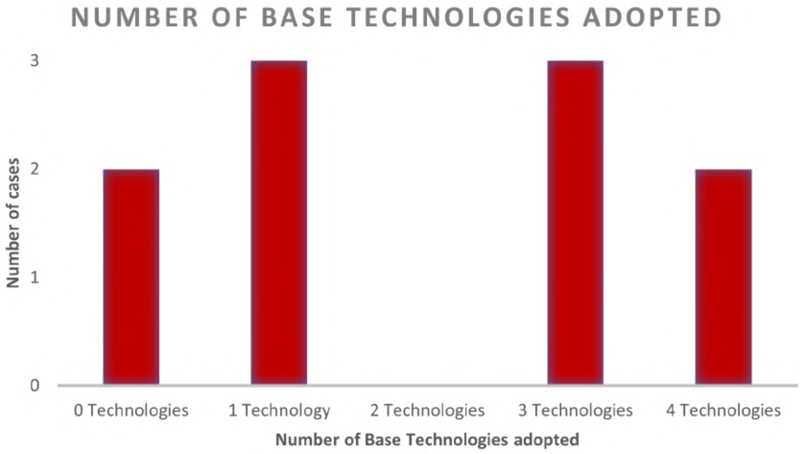
Table 8: Base technologies adoption by the case studies.

Base technologies	ELECTRO1	ELECTRO2	ELECTRO3	ELECTRO4	ELECTRO5	HOUSE1	HOUSE2	FURNI1	FURNI2	PILOT	Number of cases implementing this technology	Percentage of cases implementing this technology
Cloud Computing	X		X		X			X	X	X	6	60%
IoT					X		X			X	3	30%
Big Data	X		X		X				X	X	5	50%
Analytics	X		X	X	X				X	X	6	60%
Amount of base technologies adopted	3	0	3	1	4	0	1	1	3	4		
Rate of base technologies adopted by each case study	75%	0%	75%	25%	100%	0%	25%	25%	75%	100%		

Source: Created by the author

The manufacturing companies still have problems with the implementation of the base technologies. This can be seen in Figure 19 where two cases have not implemented any base technology and only two cases, the PILOT and ELECTRO5 cases, have implemented all four base technologies.

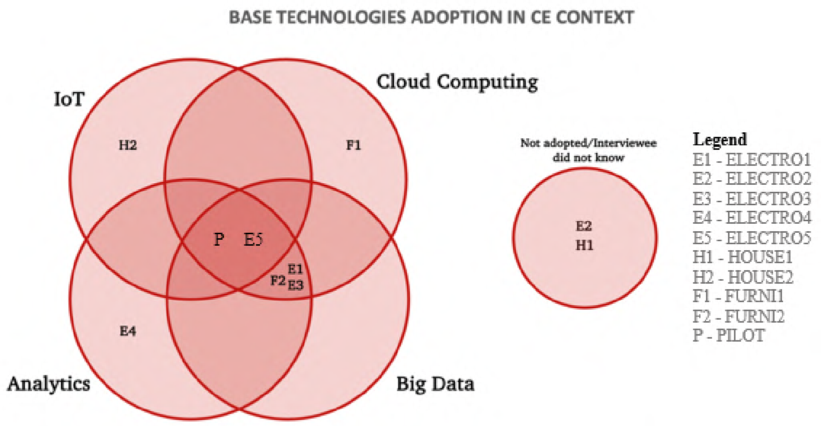
Figure 19: Number of base technologies adopted by the case studies



Source: Created by the author

The following graph shows the adoption pattern of the four base technologies in the research sample. Figure 20 illustrates that adopting cloud computing, big data and analytics jointly was more frequent than implementing any of these technologies singularly.

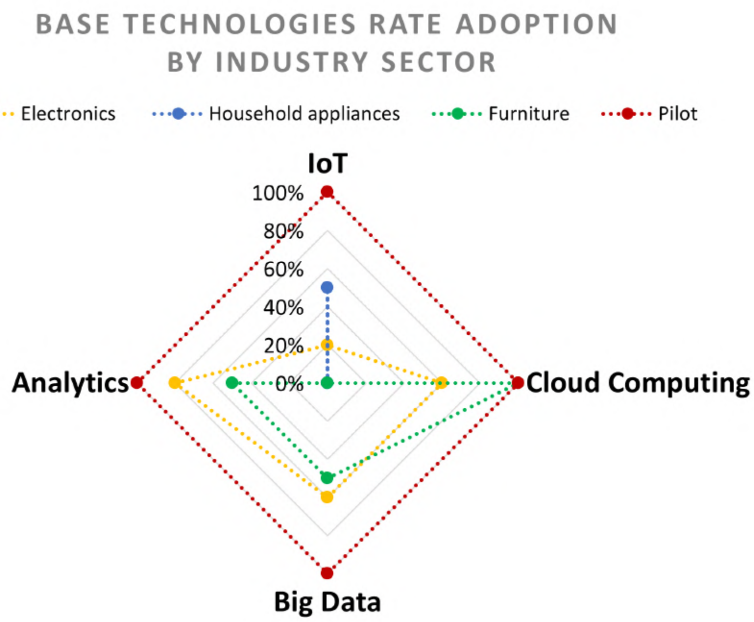
Figure 20: Base technologies adoption in the case studies



Source: Created by the author

Concerning the implementation of base technologies in different industry sectors, it was observed in Figure 21 that cloud computing was entirely incorporated in the furniture sector and in the pilot case, partially adopted in the electronics sector, and has not been implemented in the household appliances segment. When comparing this pattern to the adoption of analytics technology, it becomes evident that the furniture industry's adoption rate has decreased, and that of the electronics industry has increased. Meanwhile, the pilot case and household appliance adoption patterns remained unchanged from the cloud computing implementation. The application of big data was limited to the electronics and furniture sectors and was not implemented in the household appliances industry. Finally, with regards to the implementation of IoT, a distinct difference can be observed from the three aforementioned technologies, as the electronics and furniture industries have yet to adopt this technology, while household appliances have already done so in the context of CE.

Figure 21: Base technologies adoption rate by industry sector



Source: Created by the author

4.2.2.2 Technology radar

This section aims to comprehend the implementation of Industry 4.0 front-end and base technologies in the circular economy context and other contexts in manufacturing companies according to the framework extracted from Frank, Dalenogare e Ayala (2019). This is facilitated by creating technology radars, which are a list of technologies combined by a ring assessment result. This enables tech choices to be visualized, offering insight into the most significant industry trends (HUANG et al., 2023).

The study identified four categories of technological adoption, categorized as ADOPT, TRIAL, ASSESS, and HOLD, with specific meanings assigned to each:

- ADOPT: Technologies that the organisation has implemented in the context of the circular economy.

- TRIAL: Technologies that the organisation has successfully implemented in other contexts unrelated to CE or plans to implement in a CE context.
- ASSESS: Technologies that the organisation considers to be promising and have a clear potential to add value to the organisation. ASSESS technologies are worth investing in some research and prototyping efforts, but they are not yet planned to be adopted in the CE.
- HOLD: Technologies that the organisation does not recommend for new projects, as they are deemed unworthy of investment.

By utilising the ring assessment definitions, the industry 4.0 framework examined in the literature review chapter, and the findings from the intra-case studies analysis, Table 9 was formulated. The table presents an evaluation of the adoption of Industry 4.0 technologies in the conducted case studies, with technologies presented in order of increasing complexity level of implementation within the category as recommended by Frank, Dalenogare e Ayala (2019).

Table 9: Technology radar

I4.0 Category		ID	Technology	ELECTRO1	ELECTRO2	ELECTRO3	ELECTRO4	ELECTRO5	HOUSE1	HOUSE2	FURNI1	FURNI2	PILOT
Base technologies		B1	Cloud Computing	ADOPT		ADOPT	TRIAL	ADOPT	ASSESS		ADOPT	ADOPT	ADOPT
		B2	Internet of Things (IoT)				TRIAL	ADOPT	TRIAL	ADOPT	ASSESS		ADOPT
		B3	Big Data	ADOPT		ADOPT		ADOPT	ASSESS		TRIAL	ADOPT	ADOPT
		B4	Analytics	ADOPT		ADOPT	ADOPT	ADOPT			TRIAL	ADOPT	ADOPT
Smart Manufacturing	Vertical Integration	M1	Enterprise Resource Planning (ERP)	ADOPT	ADOPT	ADOPT		TRIAL	ASSESS				
		M2	Customer Relationship Management (CRM)	ADOPT									
		M3	Materials Requirements Planning (MRP)								ADOPT		
	Traceability	M4	Building Information Modeling (BIM)								ADOPT		
		M5	Blockchain	ASSESS						ASSESS			ADOPT
		M6	Radio Frequency Identification (RFID)								ASSESS	ASSESS	ADOPT
	Automation	M7	Robots	TRIAL			TRIAL	TRIAL	HOLD				ADOPT
		M8	Automated Guided Vehicle (AGV)										ADOPT
		M9	Automated picking systems										ADOPT
	Virtualization	M10	Artificial Intelligence (AI)	HOLD			ASSESS	ADOPT	HOLD				ADOPT
		M11	Digital worker assistance system for inspecting				ASSESS	ADOPT				ASSESS	ASSESS
		M12	Virtual simulation of processes					ADOPT					ADOPT
	Flexibility	M13	Additive manufacturing - 3D Printing					ADOPT					ADOPT
		M14	Computer-aided design (CAD)								ADOPT	ADOPT	
Smart Supply Chain		S1	Digital platforms with suppliers		ADOPT		ADOPT	TRIAL				TRIAL	ADOPT
		S2	Digital platforms with customers	ADOPT		TRIAL				ADOPT		TRIAL	
Smart Working		W1	Collaborative robots				TRIAL						ADOPT
		W2	Virtual Reality (VR) and Augmented reality (AR)					ADOPT					ADOPT

LEGEND

ADOPT
TRIAL
ASSESS
HOLD

Source: Created by the author

After classifying and evaluating the implementation of Industry 4.0 technologies in each of the case studies, a set of four technology radars was constructed, with one dedicated to each case study group.

Electronics and ICT industry

The electronics industry is facing numerous challenges, including constant technological advancements, issues related to services due to lack of background knowledge, shorter product life cycles, uncertain demand and supply, heterogeneous goods, and distributed locations. These challenges are well-documented in the literature, highlighting the complexity and dynamic nature of the sector. The electronics industry can address its challenges and improve remanufacturing capabilities by adopting Industry 4.0 technologies such as the cloud, IoT, and cyber-physical systems and RFID (WANG; WANG, 2019). The adoption of digital twin and physical internet is gaining significance in recent times. Digital twin is an enabling technology that links actual physical systems with their virtual depictions using advanced digital technologies (DEEPU; RAVI, 2021).

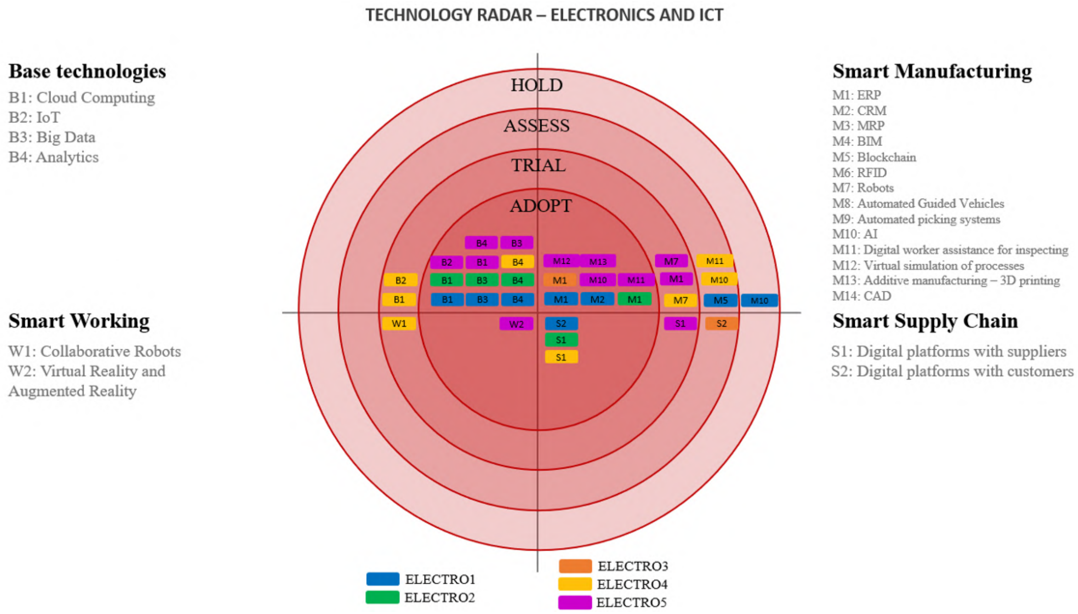
However, there are barriers that make wider implementation difficult. These include the lack of commitment and support from top management, resistance from OEMs to expose product design and technical information to the public to protect their intellectual property, and the absence of standards and execution of extended producer responsibility. Additionally, from a technological perspective, many companies lack full knowledge of the entire product lifecycle. Hence, it requires robust and easy-to-use systems to support the stakeholder's engagement with limited knowledge and experience (WANG; WANG, 2019).

The first radar is shown in Figure 22 and relates to the electronics and ICT sector. It was observed that cloud computing, big data and analytics were adopted as enabling technologies in at least three case studies, suggesting that the electronics sector recognises the value of these tools. Furthermore, the ELECTRO5 case study highlighted the key role of its already fully operational IoT-enabled digital performance management system in reducing material loss and increasing overall equipment effectiveness. In addition, the simultaneous adoption of IoT and cloud technologies within its circular economy framework has delivered significant positive environmental outcomes, manifested in reduced material loss and reduced plastic spend. The ELECTRO4 case study has also recognised IoT as a valuable technology already operational within the linear production paradigm, with the intention of integrating it into the circular production line for comprehensive product condition data collection.

Regarding Smart Manufacturing technologies, the electronics and ICT industry has already vaguely utilised vertical integration technologies such as ERP and CRM systems. Additionally, concerning automation technologies, a case study in this sector has employed collaborative robots as an automation facilitator and has discovered considerable value in virtualisation technologies like AI and digital working assistance for inspecting. In addition, Blockchain has been identified as a tool that is worth researching and investing in as it can provide competitive advantages in the near future. Nevertheless, there is still resistance to the adoption of I4.0 technologies. The interviewees expressed fears regarding job loss opportunities and some even commented on the lack of reliability of AI, which hinders its potential as a technology worth investing in.

When identifying Smart Supply Chain technology trends, it was found that the sector has already adopted digital platforms with suppliers and customers. However, a single case study is currently assessing digital platforms with customers due to the need for significant external capabilities to develop and integrate this technology. Finally, upon observing the implementation of Smart Working, it was noted that no technology has yet been introduced in the CE context, as the circular line remains largely manual in all case studies. Although one case study showed an interest in introducing collaborative robots, this is currently only at the planning stage.

Figure 22: Technology radar - Electronics and ICT



Source: Created by the author

Household appliances industry

The literature suggests that the use of digital technologies can bring many benefits to the transition towards a circular economy in the household appliances industry. However, many organisations are still hesitant to invest in these technologies due to perceived risks. The industry is currently utilizing base technologies such as IoT, big data, and cloud to support servitization business models, where appliances are offered as a service. IoT is primarily utilised for gathering data from users and billing services. big data is employed to analyse customer behaviour and cater to their needs, while cloud technology is used to enhance the sharing of appliances. It is advisable to adopt all three technologies in conjunction, as they handle with the same data. On the other hand, 3D printing is currently being used to support repair processes. It is important to note that this technology is still underdeveloped and is often used independently, without the support of the aforementioned technologies (BRESSANELLI et al., 2020).

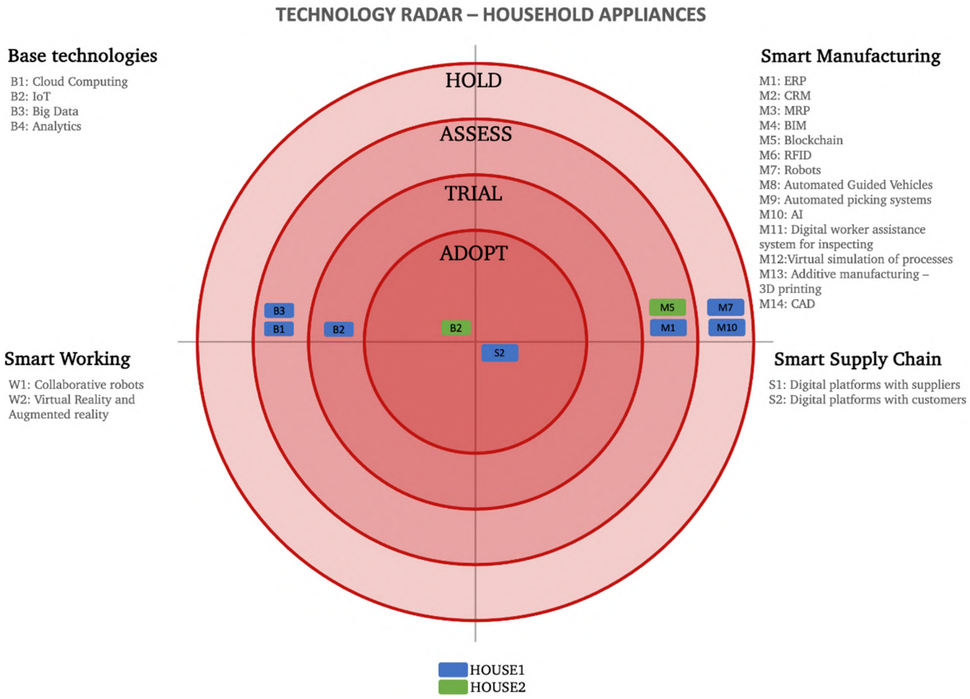
There are two adoption patterns of CE business models in the home appliances sector, the incremental and the radical adoption pattern (BRESSANELLI et al., 2020). The incremental pattern aims to improve existing products with small changes and is usually adopted by OEMs. Reduce and recycle strategies are usually adopted with the aim of extending product life, improving energy efficiency and increasing the proportion of recycled materials (especially plastics) in appliances. This adoption pattern does not usually require digital technologies due to its low implementation complexity and is the main pattern adopted by HOUSE1 and HOUSE2. On the other hand, radical patterns enable new and disruptive solutions for the market and are usually adopted by start-ups or external initiatives of large companies. Reuse, remanufacturing and sharing are the CE strategies that support this approach and digital technologies such as IoT, big data and cloud are strong enablers of these business models. This radical pattern is rarely adopted by OEMs, as it requires a lot of experimentation and has high uncertainties and high risks of success (BRESSANELLI et al., 2020). In the HOUSE2 case study, this initiative could be observed. However, as indicated in the literature, this initiative was taken by an external initiative of HOUSE2.

Figure 23 of the second radar displays the household appliances sector. One case study has adopted IoT for servitization business models, as the literature suggests, while the other is planning to adopt it within this sector. This suggests that the household appliance industry recognizes the value of IoT. Currently, the industry is attempting to enhance device connectivity, as it presents opportunities for improved resource efficiency. However, it should be noted that other technologies such as cloud computing and big data are still in the assessment stage, suggesting that digitalisation is not the current priority for this sector. One interviewee claimed that the impact of it on the CE project has been insignificant, and hence, it has not been of paramount importance. Additionally, it was noted that the interviewees possessed insufficient knowledge regarding these technologies and highlighted that the organisation is in the preliminary phases of implementing them due to the notably manual nature of their processes.

Smart Manufacturing technologies have yet to be implemented by the household appliances sector. The lack of knowledge possessed by the interviewees regarding these technologies could be the reason why the organisation is still in the initial implementation stages. This might be attributed to the fact that their processes are notably manual. However, one interviewee said that traceability technologies like blockchain can be useful in the future, but the respondent did not know precisely how to apply it yet. Furthermore, a case study revealed instances of hesitation towards automation technologies such as robots and virtualization technologies such as AI due to the belief of the respondent that their implementation in the circular line would be unachievable in the future.

When analysing the adoption of Smart Supply Chains, one case study used digital platforms with its customers, as this case study has servitization business models and these models usually require having a lot of information from the customer. However, it has been observed that both organisations face obstacles in fully adopting circular business models. Consequently, circular initiatives are not currently their top priority. Additionally, no Smart Working technologies were identified in the technology radar.

Figure 23: Technology radar - Household appliances



Source: Created by the author

Furniture industry

According to the literature on I4.0 adoption in the furniture industry, innovative technologies are crucial for the sector's future development. The application of such technologies has increased the efficiency of operations by 30-50% in the last five years since the first innovations were introduced, especially in enterprises with atypical production and large companies. It can also lead to a reduction in communication flows, error rates and repetitive operations at all levels of the company. In addition, it can help ensure the efficient use of renewable resources in line with the Sustainable Development Goals (SDGs) (ČERVENÝ; SLOUP; ČERVENÁ, 2022).

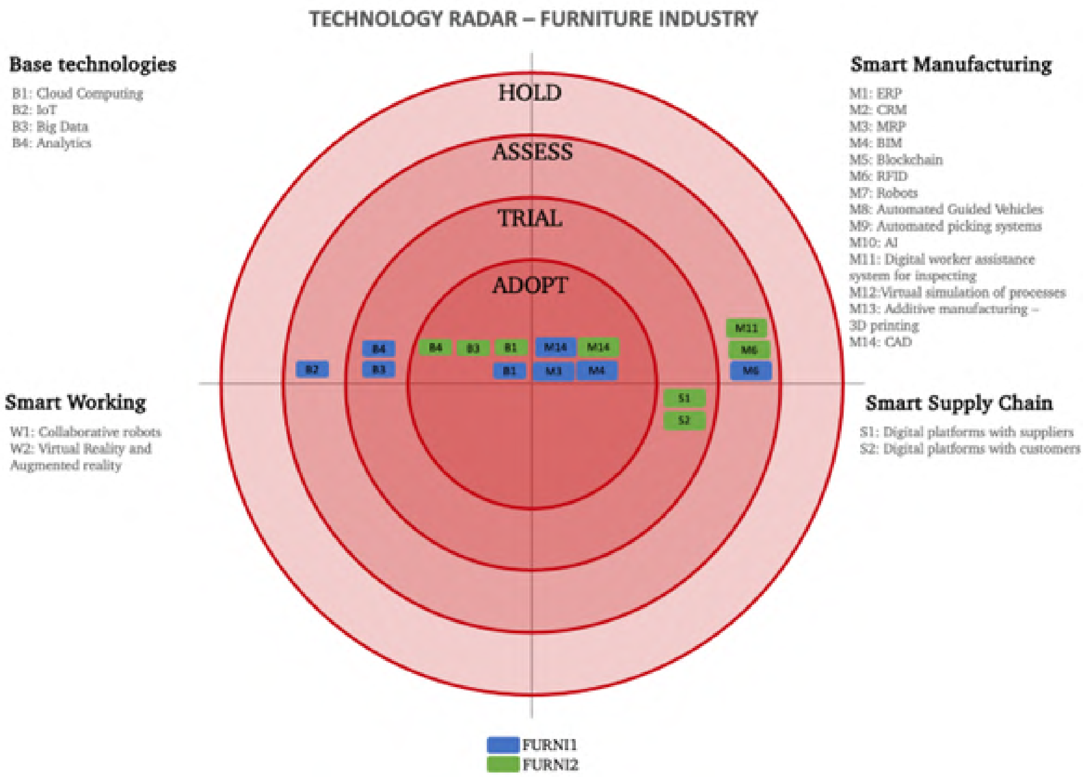
The next radar shows the technologies adopted by the furniture industry case studies. In terms of the use of core technologies, cloud computing was used in the context of CE in both case studies, and big data and analytics in one case study, as shown in Figure 24. The furniture industry considers IoT to be an ASSESS technology, as one organisation saw its value in its circular business model. They are currently conducting research on this technology for possible implementation in the future.

In terms of adoption of Smart Manufacturing technologies, this industry has adopted MRP as a vertical integration tool, CAD as a means to improve flexibility and BIM as a traceability aid. In addition, the furniture industry is looking for technologies that facilitate the traceability of its products. Both case studies showed considerable interest in RFID as an instrumental technology, as it allows product information to be stored in the product itself. In addition, a digital worker assistance system for inspection was identified as a potentially valuable technology for automating the quality assessment of the remanufacturing process, with future benefits. The literature supports the use of traceability technologies to achieve CE in the furniture industry. This is because manufacturers need detailed information at every stage and process of a product, as well as from the manufacturer to the customer. Baygin, Baygin e Karakose (2020) propose a prototype for a traceable furniture chain that uses blockchain technology to develop production based on customer demands. Blockchain is an effective solution for traceability and security issues, as demonstrated by its success in various fields.

In terms of Smart Supply Chain technologies, digital platforms with suppliers and customers were considered to be at the trial stage, as these tools have been implemented in the linear production line and are planned to be extended to the circular projects, as the adoption of this technology could significantly improve the automation of logistics within the CE processes. This industry has not yet adopted any Smart Working technologies. One possible explanation for this is that the circular processes currently rely entirely on manual work activities. This is because each returned goods case requires an individual assessment of its quality. The interviewees did not know how to incorporate these technologies into their production line.

The literature indicates that Industry 4.0 plays a significant role in achieving a circular economy. However, technological innovations are often overlooked as the primary resources required to manufacture sustainable furniture. Working with reclaimed goods primarily involves manual labour to restore the products to their original condition, as seen in the case studies of FURNI1 and FURNI2. For a successful transition, it is important for staff to be aware of their limitations and actively seek new knowledge to process reclaimed materials. Working with previously manufactured materials has consequences for how the resource is handled and reprocessed. New skills need to be acquired throughout the production cycle as the products have different origins and conditions, and each case must be analysed individually. The company should avoid relying on trial and error to achieve its goals, as this can be more time-consuming than working with stable supplies. To ensure that staff understand and embrace the company's sustainability values, management should communicate them clearly (FURN360, 2018).

Figure 24: Technology radar - Furniture industry



Source: Created by the author

Pilot case

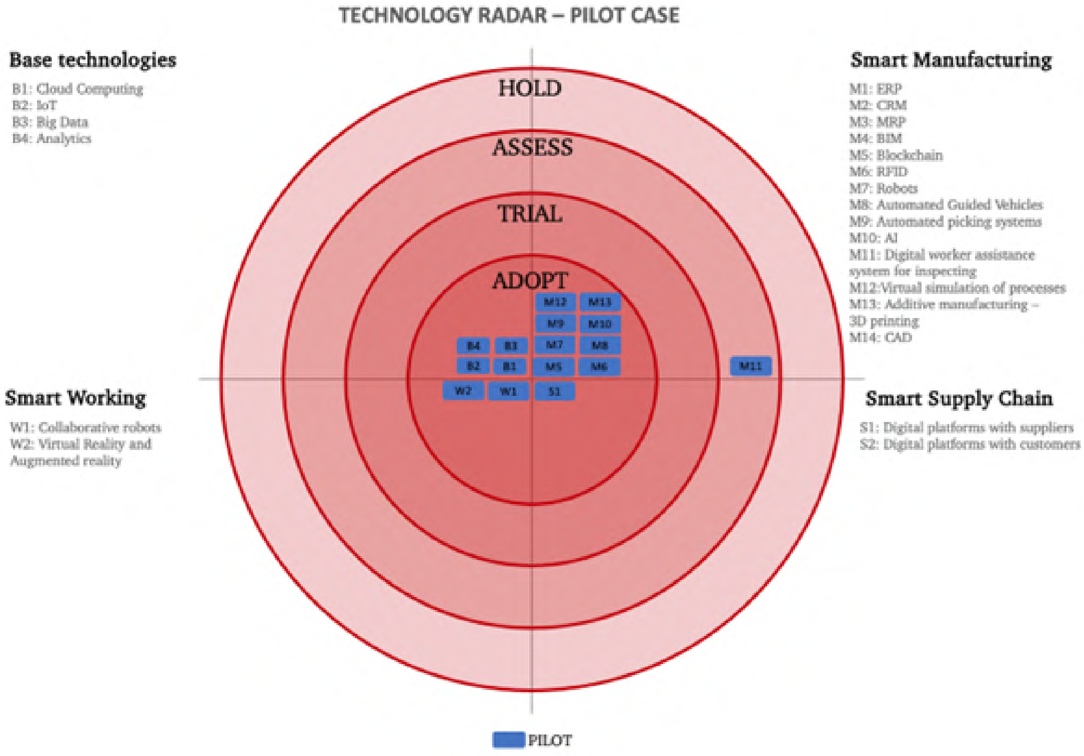
The last radar (Figure 25) concerns the PILOT case, which can be considered an advanced I4.0 adopter case, as one of the main purposes of the learning factor is to understand the requirements and benefits of I4.0 technologies. The high level of I4.0 adoption in this organisation could be attributed to the establishment of a robust delivery system that facilitated its implementation through the creation of a collaborative network for knowledge transfer and development, as suggested by Bag et al. (2018).

The PILOT case has fully implemented all the base technologies in its factory. In addition, in terms of Smart Manufacturing technologies, the pilot adopts AI and virtual simulation of processes as virtualisation tools, and robots, AGVs and automated picking systems as automation initiatives. To achieve traceability, PILOT uses blockchain and RFID, and to improve flexibility, it has implemented additive manufacturing technology. PILOT is also evaluating a digital work support system for inspection to improve the virtualisation of quality inspection processes.

When analysing the implementation of Smart Supply Chains, it was found that this organisation has implemented digital platforms with suppliers that enable information sharing between partners, making collaboration easier and more effective. Finally, in terms of Smart Working tools, PILOT uses collaborative robots and virtual and augmented reality in its circular production lines. PILOT was the only case study that adopted Smart Working technologies within the circular production and this is in line with Frank, Dalenogare e Ayala (2019).

The case study has implemented various Industry 4.0 technologies across all I4.0 technology groups. This is in line with the contributions to Frank, Dalenogare e Ayala (2019) that showed that advanced adopters usually adopt all technologies, rather than just some specific ones. This demonstrates that growing maturity in I4.0 adoption requires the aggregation of many different technologies, rather than substituting one technology for another. As shown in Figure 4, when companies incorporate new and more complex technologies, they contribute to a higher level of Industry 4.0 adoption and maturity.

Figure 25: Technology radar - Pilot case



Source: Created by the author

Comparison across industry sectors

After presenting each technology radar for each specific manufacturing industry group, this section presents the comparison of I4.0 adoption in the context of circular economy across industries. When comparing the adoption of Smart Manufacturing between the groups, the pilot case study has the highest implementation of technologies, adopting technologies from all categories of Smart Manufacturing. The electronics and furniture sectors have an intermediate implementation of these technologies, as the electronics industry case studies have adopted some vertical integration tools, have tried automation tools and are evaluating traceability and virtualisation tools, and the furniture industry case studies have adopted vertical integration, traceability and flexibility technologies and are evaluating virtualisation tools. The furniture industry can be considered as having a higher level of implementation than electronics because it has adopted higher complexity categories of Smart Manufacturing such as flexibility technologies and also in the electronics sector it was noted that there is more resistance to technology adoption because artificial intelligence is classified as a "HOLD" technology by one case study because the company cannot trust AI and it is associated with a high risk.

On the other hand, the household appliances sector has the lowest adoption of Smart Manufacturing technologies in the CE context, because it has not fully adopted any Smart Manufacturing tools and is only evaluating vertical integration and traceability tools and has resistance to automation and virtualisation tools. This can be explained by the fact that circular solutions in this sector are mainly incremental innovations and do not require the use of high technology, being less complex. Moreover, it can be observed that the Smart Manufacturing adoption in all manufacturing segments slightly follows the I4.0 adoption patterns suggested in Figure 4, since, excluding the pilot case, the vertical integration tools are the most adopted category with 5 tool adoptions, followed by the flexibility category with 2 adoptions and then the traceability category with 1 adoption.

Regarding the adoption of base technologies, it was observed that the more advanced the company is in Smart Manufacturing technologies, the stronger the presence of basic technologies, as suggested by Frank, Dalenogare e Ayala (2019). Therefore, it is observed that the pilot case study has the highest adoption of base technologies, followed by the furniture and electronics sector with an intermediate adoption and then the household appliances sector with the lowest adoption of base technologies. Furthermore, the pattern of I4.0 adoption suggested by Frank, Dalenogare e Ayala (2019), where IoT, cloud computing, big data and analytics are ranked according to their implementation complexity, was not followed. Cloud computing and analytics were the most adopted in the case study sample with 5 implementations each, followed by big data with 4 implementations and IoT with 2 implementations.

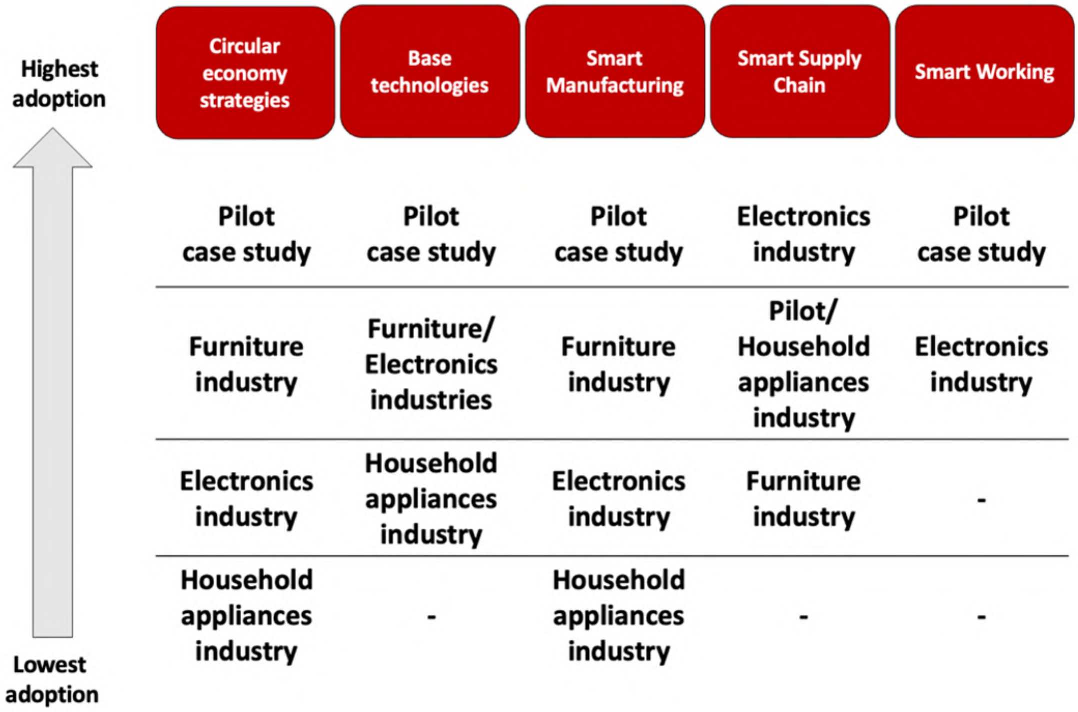
When analysing the use of Smart Supply Chain technologies in the case studies, it is observed that the pilot case study has only implemented digital platforms with suppliers and not with customers, as it did not have any customers. When comparing with other groups, it is noted that the electronics sector has the highest adoption of Smart Supply Chain tools, having implemented both digital platforms with suppliers and customers. The household appliances sector has intermediate adoption, as it has servitization business models that require platforms to obtain useful data from product usage. In contrast, the furniture industry has not adopted any Smart Supply Chain tools within the CE context. Besides that, in the sample of case studies it is noted that digital platforms with suppliers are more commonly adopted than those with customers, suggesting that they may be easier to implement and a potential first step towards horizontal integration. This follows the high complexity implementation pattern identified by Frank, Dalenogare e Ayala (2019).

Finally, regarding Smart Working technologies, only the pilot case has implemented them, and the electronics industry is still in the trial stage. This is in line with Frank, Dalenogare e Ayala (2019) who found that advanced I4.0 adopters, such as the pilot case, were strongly more likely to implement these tools than intermediate or lower I4.0 adopters.

Furthermore, Figure 26 displays the most advanced adopters of circular economy strategies and Industry 4.0 technologies. When comparing the most advanced adopters of circular economy strategies, base technologies, and smart manufacturing, it is evident that the pilot case was the most advanced adopter, followed by the furniture, electronics, and household appliances group. A higher implementation of circular economy principles can be achieved through the implementation of higher level base technologies and smart manufacturing.

Moreover, it can be inferred that the use of base technologies can facilitate the implementation of Smart Manufacturing technologies, as proposed by Frank, Dalenogare e Ayala (2019). This is due to the fact that both types of technologies exhibit similar patterns of adoption across various industry groups. However, the adoption of Smart Supply Chain and Smart Working technologies does not follow the same trend as other technologies and strategies related to circular economy. Frank, Dalenogare e Ayala (2019) also note that advanced adopters typically lead all Industry 4.0 technology groups. This is in line with the observation that the pilot case has the highest adoption rate of all technologies across all industry sectors, except for the Smart Supply Chain. This is because, as the pilot case study does not have customers, there is no need to use digital platforms with customers.

Figure 26: Most advanced industry sector adopters for circular economy strategies and I4.0 technologies



Source: Created by the author

4.2.2.3 Barriers to I4.0 adoption in circular business models

Despite the progress of I4.0 technologies in linear production lines, many industries are still reluctant to implement them in their circular business due to the additional barriers imposed by the circular business models (K et al., 2023). Table 8 presents the principal barriers identified in the sample of case studies. The barriers are extracted from K et al. (2023). The PILOT case was excluded from this analysis because, as a university rather than a company, it does not make sense to analyse it together with the other case studies.

The most common barrier in the sample was related to the limited scalability of CBM when compared to linear business models. This is due to the novelty of these business models, which creates uncertainty around the technical and financial resources available. The lack of scalability in Industry 4.0 may also be attributed to poor technology implementation (K et al., 2023). This barrier can be analysed well in the FURNI2 case study. The interviewee reported that due to the limited reach of CE initiatives, there are limited resources working on them. This difficulty leads to a narrower scalability of these initiatives and, consequently, the implementation of new technologies.

It can be observed that in seven out of eight case studies, there was a lack of a consistent roadmap for the implementation of Industry 4.0. Ineffective planning is a significant barrier to the adoption of Industry 4.0, and without a well-defined strategy, successful implementation is highly unlikely. For the strategy to be effective, it is necessary to consider both technical and financial aspects (SWAN, 2018). The case study from ELECTRO4 stands out from the rest of the studies, as it demonstrates the company's strategic approach to implementing I4.0 technologies. This includes partnerships with universities to assist with implementation, leveraging their technical expertise.

In six out of eight organisations, a common barrier is the difficulty and complexity of changing organisational culture. This is due to the focus on short-term goals that demand quick results, which can limit the implementation of new policies and hinder changes to workflow (TÖNNISSEN; TEUTEBERG, 2020). Organisations must develop new policies or guidelines and gain a thorough understanding of Industry 4.0 implementation to effect change effectively (SWAN, 2018). In the FURNI2 case, the interviewee reported that CE initiatives and technology improvements were deprioritised. This was due to their association with longer-term goals and the relative newness of the company, which is currently focused on running the business. In the FURNI1 case, the respondent noted that it was initially challenging to persuade senior management to establish targets and performance indicators for remanufactured products. This was due to their lack of conviction in the value of circular economy initiatives, which hindered the development of technologies in this area.

The next barrier is the lack of knowledge expertise and awareness of digital technology implementation. Some organisations lack plans to implement digitalisation at all levels of the organisation's supply chain, and there are few standard tools, which impose additional challenges for Industry 4.0 (MANAVALAN; JAYAKRISHNA, 2019). The case studies ELECTRO2 and ELECTRO3 revealed that the interviewees had limited knowledge of I4.0 adoption, suggesting that their organisations may lack awareness of technology adoption. Similarly, in the HOUSE2 case, the respondent noted a lack of standards for CE solutions, which may hinder the adoption of standard tools for these initiatives.

The immaturity of technology due to lack of development is often an obstacle to implementing Industry 4.0 technology on a large scale. Many organisations have not yet upgraded to the latest technologies. Furthermore, certain industries may be unaware of the latest technological advancements, which can indirectly lead to security challenges and a negative perception of technology (KOUHIZADEH; SABERI; SARKIS, 2021). In the case studies related to the furniture sector, it was noted that respondents had difficulty in applying Industry 4.0 technologies, particularly automation and virtualization technologies. This is due to the highly manual manufacturing processes currently used in the furniture industry. However, the household appliances industry has already widely applied Industry 4.0 to linear production lines. Therefore, the respondents did not show this difficulty.

The following barrier concerns the lack of infrastructure. Some organisations do not have an up-to-date system infrastructure necessary to handle and incorporate diverse components or devices (JAEGER; UPADHYAY, 2020). The absence of a well-developed infrastructure plays an important role in enabling the implementation of Industry 4.0. Without it, interfacing different components in the system would be challenging, thereby impeding interaction with the physical world(BISWAS; GUPTA, 2019). The ELECTRO3 and FURNI2 case studies encounter this challenge due to their limited financial and technical resources for infrastructure updates.

In two case studies, an additional obstacle was the high dependence on third-party technology providers. These companies did not have the necessary IT resources and infrastructure with the latest technologies to develop their technology internally (YADAV et al., 2020). This was observed in the ELECTRO2 and ELECTRO3 organisations, which had to hire external companies to develop technologies for them because they lacked this capability.

The introduction of I4.0 technologies has led to workers fearing job loss, as noted by Luthra, Mangla e Yadav (2019). Possible reasons for job insecurity and disruption may include a lack of awareness of sustainability and a failure to adapt to the needs of the supply chain due to insufficient knowledge of new technology adoption (SUÁREZ-EIROA; FERNÁNDEZ; MÉNDEZ, 2021). The respondents' resistance towards adopting I4.0 due to job loss insecurity was evident in ELECTRO1 and ELECTRO2.

Table 10: Barriers of I4.0 adoption.

Barrier	Description	ELECTRO1	ELECTRO2	ELECTRO3	ELECTRO4	ELECTRO5	HOUSE1	HOUSE2	FURNI1	FURNI2	Number of cases affected	Impact rate of each barrier
Limited scalability	Companies adopting CE approaches may have a barrier against I4.0 adoption, due to the limited scability in their business models, since usually there is an insecurity on technical and financial resources available. Another possible cause for limited scalability may be the insufficient progress in technology towards Industry 4.0 application.	X	X	X	X		X	X	X	X	8	89%
Lack of roadmap for successful implementation of Industry 4.0	Companies adopting CE approaches may not have a well-defined strategy for I4.0 implementation, which could be an obstacle for its adoption. Organisations require a strategy that comprehends the principles and fundamentals of Industry 4.0, taking into account necessary technological and financial resources.	X	X	X			X	X	X	X	7	78%
Difficulty and complexity in changing organizational culture	Companies adopting CE approaches may have a barrier against I4.0 implementation, due to the difficulty in changing the organization structure. Organisations often focus on short-term goals that demand quick results, which can limit the implementation of new policies and hinder changes to their workflow. There is a need for organizations to come up with the change in policies or define a new set of guidelines and also would need to develop a better understanding within themselves so that it would create an effective change in Industry 4.0		X	X			X	X	X	X	6	67%
Lack of knowledge expertise and awareness on digital technology implementation	Companies adopting CE approaches need proactive plans to implement digitisation across all organisational hierarchies in the supply chain. There is also a lack of standard tools and business models, which poses a challenge to the adoption of Industry 4.0. Some companies don't have the basic principles of I4.0 and therefore don't realise the benefits of implementing it.		X	X			X	X		X	5	56%
Immaturity of technology	Companies adopting CE appoaches may have a barrier against I4.0 adoption, due to lack of development in technology. It is often challenging to implement Industry 4.0 technology on a large scale, and a significant number of organisations have not yet upgraded to the latest technologies. Additionally, some industries remain unaware of the latest tools, which have indirectly contributed to security challenges and a negative perception of technology.		X	X					X	X	4	44%
Lack of infrastructure	Companies adopting CE approaches may not possess an up-to-date system infrastructure necessary to handle and incorporate diverse components or devices. The absence of a well-developed infrastructure plays an important role in enabling the implementation of I4.0, as it would be challenging to interface different components in the system without it, thereby impeding interaction with the physical world.			X						X	2	22%
Dependent on 3rd party technology providers	Companies that adopt CE approaches may encounter obstacles in adopting I4.0 due to their current lack of equipped IT resources and infrastructure with the latest technologies. Consequently, these organizations highly depend on third-party providers to implement I4.0.		X	X							2	22%
Disruption to existing jobs	Companies adopting CE approaches may hinder the implementation of Industry 4.0 due to employee fears of losing their jobs. Potential reasons for job insecurity and disruption may include insufficient consideration of sustainability and failure to adapt to the needs of the supply chain.	X	X								2	22%
	Total barriers amount	3	7	7	1	0	4	4	4	6		
	Rate of barriers affecting each case study	38%	88%	88%	13%	0%	50%	50%	50%	75%		

Source: Created by the author

4.2.3 Assessment CE Maturity and I4.0 Readiness

Although Industry 4.0 undoubtedly benefits firms by improving the economic performance of plants and supply chains (RAJ et al., 2020), there is still a lack of a structured and practical model that integrates I4.0 and the circular economy, taking into account the specific variables that characterise real manufacturing firms (SPALTINI; ACERBI; TAISCH, 2022). To address this gap, this section proposes a tool to assess both Industry 4.0 Readiness (I4R) and CE maturity in manufacturing firms based on various aspects. The proposed framework can be used by researchers to assess I4R and CE focus in a manufacturing firm, and organisations can use this framework as a self-assessment tool.

4.2.3.1 Assessing the Circular Economy Maturity

The first step involved collecting qualitative information about the adoption of CE within the organization. To address this, the following question was posed: "How would you classify the adoption of CE in your company?". This question aimed to gauge the interviewee's perception of CE adoption within the organization.

Respondents could choose from five possible answers, each corresponding to a specific value ranging from 0% to 100%. The possible responses for the first question were: "Not adopted (0%)," "Starting to consider adoption (25%)," "Planning adoption (50%)," "Adopted (75%)," and "Fully adopted (100%)". Some interviewees responded with "Between planning and adopted," for which an intermediate value of 67.5% was assigned. After collecting the answers, the first variable of the CE Index addressing the perception of CE adoption in the company was derived. Table 11 presents the interviewees' responses to the adoption of CE for each organization.

Table 11: CE Index Variable 1: Perception of CE adoption in the company

Case Study	**Quesion 1:** Adoption of circular economy in the company	**Variable 1:** Perception of CE adoption in the company
ELECTRO1	Fully adopted	100%
ELECTRO2	Fully adopted	100%
ELECTRO3	Fully adopted	100%
ELECTRO4	Adopted	75%
ELECTRO5	Adopted	75%
HOUSE1	Planning adoption	50%
HOUSE2	Planning adoption	50%
FURNI1	Planning adoption	50%
FURNI2	Between planning adoption and adopted	67,5%
PILOT	Between planning adoption and adopted	67,5%

Source: Created by the author

The second step involved gathering qualitative information about the relative importance of circular economy compared to other competitive manufacturing capabilities. To address this, the following question was posed: "How important is circular manufacturing for your company compared to other competitive manufacturing capabilities?".

Similarly to the first question, respondents could choose from five possible answers, each corresponding to a specific value ranging from 0% to 100%. For the second question, the possible responses were: "Not at all important (0%)," "Low importance (25%)," "Neutral (50%)," "Important (75%)," and "Very important (100%)." Subsequently, the second variable of the CE Index that measures the relative importance of CE when compared to other manufacturing capabilities was created. Table 12 presents the results for each organization.

Table 12: CE Index Variable 2: Relative importance of CE compared to other competitive manufacturing capabilities

Case Study	**Question 2:** Importance of circular manufacturing when compared with with other competitive manufacturing capabilities in the company	**Variable 2:** Relative importance of CE compared to other competitive manufacturing capabilities
ELECTRO1	Very important	100%
ELECTRO2	Very important	100%
ELECTRO3	Very important	100%
ELECTRO4	Very important	100%
ELECTRO5	Very important	100%
HOUSE1	Important	75%
HOUSE2	Important	75%
FURNI1	Very important	100%
FURNI2	Important	75%
PILOT	Very important	100%

Source: Created by the author

The third step involved collecting qualitative data on the implementation of CE strategies by the manufacturing company. The formulated question to address this was as follows: "According to the information provided in the support material, could you please classify which of the following CE strategies your company adopts and how these concepts have been implemented by the company?". The possible responses encompassed the strategies within the 9R circular strategies framework.

In order to calculate the third variable of the CE Index, it was first necessary to determine the number of VRP strategies and non-VRP strategies that had been adopted. The ratio of VRP strategies that have been adopted was then calculated by dividing the number of adopted VRP strategies by the total number of VRP strategies available, which is four. Similarly, the ratio of non-VRP strategies that have been adopted was calculated by dividing the number of adopted non-VRP strategies by the total number of non-VRP strategies available, which is six.

Subsequently, the VRP adoption ratio was multiplied by a factor of two, while the non-VRP adoption ratio was multiplied by a factor of one. The third variable of the CE Index was then derived by summing these weighted ratios and dividing the total by three (Table 13). The VRP strategy adoption was assigned a higher weighting because VRP practices are preferable as they extend the lifespan of products and their parts, while maintaining or improving their value.

Table 13: CE Index Variable 3: CE strategies adoption rate

Case Study	**Amount of VRP strategies adopted**	**Amount of non-VRP strategies adopted**	**VRP adoption ratio**	**Non-VRP adoption ratio**	**Variable 3:** CE strategies adoption rate
ELECTRO1	4	2	100%	33%	67%
ELECTRO2	3	1	75%	17%	46%
ELECTRO3	3	1	75%	17%	46%
ELECTRO4	3	2	75%	33%	54%
ELECTRO5	4	2	100%	33%	67%
HOUSE1	3	2	75%	33%	54%
HOUSE2	2	2	50%	33%	42%
FURNI1	4	1	100%	17%	58%
FURNI2	3	3	75%	50%	63%
PILOT	4	4	100%	67%	83%

Source: Created by the author

The fourth step involved the combination of the three variables to derive the CE Maturity Index. In order to achieve this, the first and the second variables were multiplied by a factor of 1, and the third variable by a factor of 3. The rationale for attributing a higher weight to the third variable is that it provides a more objective and measurable assessment of the actual implementation of CE strategies, since it is based on tangible actions and practices within the organisation, thereby reducing the influence of personal perceptions or biases that can affect the first and the second variable assessments. Subsequently, the CE Maturity Index was calculated by summing the weighted products and dividing by 5. Subsequent to this computation, the CE Maturity Status was ascertained based on the CE Maturity Index. Potential statuses encompassed "Business as usual" (0%-25%), "CE Beginner" (26%-50%), "CE Fast Adopter" (51%-75%), and "CE Leader" (76%-100%). Table 14 delineates the CE Maturity Index and corresponding status for each case study.

Table 14: Circular Economy Maturity Index and Status

Case Study	**Variable 1:** Perception of CE adoption in the company	**Variable 2:** Relative importance of CE compared to other competitive manufacturing capabilities	**Variable 3:** CE strategies adoption rate	CE Maturity Index	CE Maturity Status
ELECTRO1	100%	100%	67%	80%	CE Leader
ELECTRO2	100%	100%	46%	68%	CE Fast adopter
ELECTRO3	100%	100%	46%	68%	CE Fast adopter
ELECTRO4	75%	100%	54%	68%	CE Fast adopter
ELECTRO5	75%	100%	67%	75%	CE Fast adopter
HOUSE1	50%	75%	54%	58%	CE Fast adopter
HOUSE2	50%	75%	42%	50%	CE Beginner
FURNI1	50%	100%	58%	65%	CE Fast adopter
FURNI2	67,5%	75%	63%	66%	CE Fast adopter
PILOT	67,5%	100%	83%	84%	CE Leader

Source: Created by the author

4.2.3.2 Assessing the Industry 4.0 Readiness

Analogous to the assessment of CE maturity, the first step entailed collecting qualitative information about the adoption of Industry 4.0 within the organization. The research protocol included the question, "How would you classify the adoption of Industry 4.0 technologies in your company?" to capture the interviewees' perceptions of Industry 4.0 implementation. The respondents had the following possible responses: "Not adopted (0%)," "Starting to consider adoption (25%)," "Planning adoption (50%)," "Adopted (75%)," and "Fully adopted (100%)". One interviewee responded with "Between planning and adopted," for which an intermediate value of 67.5% was assigned. Table 15 shows the first variable of the Industry 4.0 Readiness Index based on the answers from this question.

Table 15: I4R Index Variable 1: Perception of I4.0 adoption in the company

Case Study	**Question:** Adoption of Industry 4.0 in the company	**Variable 1:** Perception of I4.0 adoption in the company
ELECTRO1	Between planning and adopted	67,5%
ELECTRO2	Not adopted	0%
ELECTRO3	Not adopted	0%
ELECTRO4	Planning adoption	50%
ELECTRO5	Fully adopted	100%
HOUSE1	Not adopted	0%
HOUSE2	Starting to consider adoption	25%
FURNI1	Not adopted	0%
FURNI2	Not adopted	0%
PILOT	Fully adopted	100%

Source: Created by the author

The second step involved establishing the second variable for the Industry 4.0 Readiness Index by evaluating the implementation of both base and front-end technologies across each case study. This assessment was facilitated using a methodology derived from the technology radar outlined in Table 9, which categorized the adoption level of each technology into four distinct stages. A scoring mechanism was devised, assigning a value of 1 point to technologies classified as “ADOPT,” 0.5 points to those categorized as “TRIAL,” 0.25 points to “ASSESS,” and 0 points to “HOLD.” This scoring system was separately applied to both base and front-end technologies, generating their respective scores.

Subsequently, these scores were normalized by dividing each by the maximum possible score for base technologies (4) and front-end technologies (18), respectively, yielding the base technology adoption ratio and the front-end technology adoption ratio. The second variable was then calculated by averaging these two ratios as seen in Table 16.

Although base and front-end technologies were equally weighted in this average, each base technology type had a greater impact on the second variable of the Industry 4.0 Readiness Index due to the smaller number of base technology types (4) compared to front-end technology types (18). The rationale for this approach is that base technologies provide the essential infrastructure and foundational capabilities that enable the effective functioning of front-end technologies (FRANK; DALENOGARE; AYALA, 2019). Without robust base technologies, front-end technologies may not function optimally or at all. Therefore, it is logical to attribute a higher weight to each specific base technology compared to each front-end technology when forming the index.

Table 16: I4R Index Variable 2: I4.0 technologies adoption rate

Case Study	Base technologies points (maximum 4)	Front-end technologies points (maximum 18)	Base technologies ratio	Front-end technologies ratio	Variable 2: I4.0 technologies adoption rate
ELECTRO1	3	3,75	75%	21%	48%
ELECTRO2	0	2	0%	11%	6%
ELECTRO3	3	1,5	75%	8%	42%
ELECTRO4	2	2,5	50%	14%	32%
ELECTRO5	4	6,5	100%	36%	68%
HOUSE1	1	0,25	25%	1%	13%
HOUSE2	1	1,25	25%	7%	16%
FURNI1	2,25	3,25	56%	18%	37%
FURNI2	3	2,5	75%	14%	44%
PILOT	4	9,25	100%	51%	76%

Source: Created by the author

The third step involved composing the Industry 4.0 Readiness (I4R) Index and Status, as illustrated in Table 17. The I4R Index was calculated by assigning a weight of 1 to the first variable and a weight of 2 to the second variable, and then dividing the sum of these weighted values by 3. The second component was given greater weight because, while the I4.0 adoption perception data is valuable for understanding context and attitudes, it is inherently subjective. By prioritizing the I4.0 technologies adoption rate, the overall index becomes less susceptible to individual biases and more reliable as a measure of technological maturity. Subsequently, the I4R Status was determined based on the I4R Index. The potential statuses included “Hesitators” (0%-25%), “Potentialists” (26%-50%), “Experienced” (51%-75%), and “Leaders” (76%-100%).

Table 17: Industry 4.0 Readiness Index and Status

Case Study	**Variable 1:** Perception of I4.0 adoption in the company	**Variable 2:** I4.0 technologies adoption rate	I4R Index	I4R Status
ELECTRO1	67,5%	48%	54%	Experienced
ELECTRO2	0%	6%	4%	Hesitators
ELECTRO3	0%	42%	28%	Potentialists
ELECTRO4	50%	32%	38%	Potentialists
ELECTRO5	100%	68%	79%	Expert
HOUSE1	0%	13%	9%	Hesitators
HOUSE2	25%	16%	19%	Hesitators
FURNI1	0%	37%	25%	Hesitators
FURNI2	0%	44%	30%	Potentialists
PILOT	100%	76%	84%	Expert

Source: Created by the author

4.2.3.3 Assessment tool to transition to a Circular Economy-focused Industry 4.0 setting

Based on these two assessment frameworks and the proposed analysis, Figure 27 provides a schematic representation of the possible combinations a practitioner may encounter regarding a company's Industry 4.0 Readiness and Circular Economy Maturity. The proposed matrix illustrates various combinations, including some that are improbable. For instance, it is unlikely that an I4.0 Hesitator will be a CE Leader. Once an investigator completes the analysis or a firm conducts a self-assessment, this matrix can be utilized to position the firm within the CE-I4R matrix, offering a clear visual representation of its status in both dimensions.

This matrix offers a detailed classification of ten case studies based on their Circular Economy Maturity and Industry 4.0 Readiness statuses. Several key insights can be derived from this classification. Firstly, PILOT exemplifies strategic alignment between CE and I4.0, indicating significant resource allocation and a strategic focus on integrating both Industry 4.0 technologies and circular economy principles. This alignment underscores a comprehensive approach to innovation and sustainability, setting a benchmark for other firms.

Figure 27: Circular Economy-focused Industry 4.0 Readiness Matrix

		Status of CE Maturity			
		Business as Usual (0% - 25%)	CE Beginners (26% - 50%)	CE Fast Adopters (51% - 75%)	CE Leaders (76% - 100%)
Industry 4.0 Readiness Status	Expert/ Frontrunner (76%-100%)			**ELECTRO5**	I4.0 and CE Champion **PILOT**
	Experienced (51% - 75%)				**ELECTRO1**
	Potentialists (26% - 50%)			**ELECTRO3 ELECTRO4 FURNI2**	
	Hesitators (0% -25%)	I4.0 and CE Novice	**HOUSE2**	**ELECTRO2 HOUSE1 FURNI1**	

Source: Created by the author

Moreover, a detailed gap analysis reveals areas for potential improvement. For instance, ELECTRO5, categorized as Expert in I4.0 adoption but only a CE Fast Adopter, should focus on enhancing its circular economy initiatives to progress towards CE Leadership. Conversely, ELECTRO1, a CE Leader but only an Industry 4.0 Experienced, could benefit from advancing its technological capabilities to fully leverage its Industry 4.0 potential. Firms positioned in intermediate categories, such as ELECTRO3, ELECTRO4, and FURNI2, exhibit a balance between CE and I4.0 readiness. These firms are at a crucial juncture where integrating advanced Industry 4.0 technologies could significantly accelerate their Circular Economy initiatives, thereby enhancing overall sustainability and operational efficiency. The classification also identifies HOUSE2 as a laggard, positioned as both a CE Beginner and an I4.0 Hesitator. This highlights the need for targeted interventions, such as investment in foundational technologies and introductory CE practices, to initiate progress towards higher maturity in both areas.

Furthermore, the detailed comparison of the matrix presented in Figure 27 with the adoption of circular economy strategies (Table 5) and the technology radar (Table 9) reveals significant insights. Organizations such as ELECTRO1, ELECTRO5, and PILOT, positioned in the "green zone" of high CE Maturity and I4.0 Readiness levels, demonstrate a high adoption rate of various CE strategies. These include all four VRP strategies of Reuse, Repair, Refurbish, and Remanufacture, with an average CE strategy adoption rate exceeding 60%, as indicated in Table 5. Moreover , as seen in Table 9 these organizations also adopt a broad range of advanced technologies, such as Cloud Computing, IoT, big data, ERP, and CAD, indicating a strong integration of CE strategies with I4.0 technologies. This suggests that high CE maturity and I4.0 readiness correlate with the adoption of a wide array of advanced technologies and CE strategies.

Conversely, firms like ELECTRO3, ELECTRO4, and FURNI2, positioned in the "orange zone" of the matrix and classified as CE Fast Adopters and I4.0 Potentialists, show moderate adoption rates of CE strategies. The organizations only adopt three VRP strategies and have an average CE adoption rate ranging from 40% to 60%, significantly lower than the previous group as stated in Table 5. Additionally, many advanced technologies are in the trial or assessment phase, including IoT, AI, and VR/AR as indicated in Table 9. This cautious approach towards adopting new technologies correlates with their moderate CE maturity and I4.0 readiness, highlighting the need for further integration of technologies with CE strategies.

On the other end of the spectrum, firms located in the "red zone" of the matrix such as HOUSE1, HOUSE2, ELECTRO2, and FURNI1, positioned as CE Beginners or CE Fast Adopters and categorized as Hesitators in I4.0 readiness, exhibit lower adoption rates of CE strategies, varying from 40% to 60%, and adopt fewer VRP strategies, typically two or three as mentioned in Table 5. They also show minimal adoption of advanced technologies as seen in Table 9. This minimal integration of CE strategies and technologies reflects their initial stages of development in these areas.

Therefore, the correlation analysis indicates that organizations with higher maturity levels in both CE and I4.0 are more likely to adopt a comprehensive range of advanced technologies and CE strategies. In contrast, those with lower maturity levels show limited adoption and integration, reflecting their nascent stages of development in these areas. By integrating these insights into their strategic planning, firms can better align their technological and sustainability efforts, ensuring a balanced and comprehensive approach to achieving higher levels of CE maturity and I4.0 readiness.

Sector-specific trends are also evident, with a concentration of electronics sector firms in similar areas of the matrix. This suggests common challenges or opportunities in adopting CE and I4.0 practices within the sector. Understanding these trends can help tailor industry-specific strategies for improvement. In the household appliances sector, HOUSE1 exhibits Hesitators traits in Industry 4.0 readiness but is categorized as a CE Fast Adopter, signaling initial steps in sustainability but minimal progress in digital transformation. Additionally, HOUSE2 is also identified as a Hesitator in I4.0, but as a CE Beginner, indicating substantial barriers to overcome for improvement.

Moving to the furniture industry, FURNI1 mirrors HOUSE1's Hesitator status in I4.0 and CE Fast Adopter categorization, highlighting early efforts in both areas but a need for a more integrated strategy. On the other hand, FURNI2 emerges as a Potentialist in I4.0 but a CE Fast Adopter, suggesting notable progress in sustainability initiatives yet lagging in digital transformation. This dichotomy emphasizes the importance for furniture firms to pursue balanced growth through a comprehensive approach encompassing both Industry 4.0 technologies and Circular Economy principles.

The absence of firms in certain combinations, such as the lack of CE Leaders among I4.0 Hesitators, underscores potential implementation barriers. Achieving high CE maturity is challenging without foundational Industry 4.0 technologies, highlighting the importance of a robust technological base for sustainable practices. Firms like PILOT and ELECTRO5 could serve as benchmarks or role models. Analyzing their strategies and practices can provide valuable insights and best practices for other companies aiming to improve their CE and I4.0 statuses. Furthermore, the distribution of firms across the matrix indicates that achieving high levels of both CE maturity and I4.0 readiness often requires transformational change rather than incremental improvements. Firms in lower quadrants may need to adopt radical innovations and comprehensive strategies to advance significantly.

In conclusion, the matrix highlights the complex interplay between technological readiness and circular economy maturity, offering insights into strategic priorities, sector-specific challenges, and potential pathways for improvement. By understanding these dynamics, manufacturers can better navigate their Industry 4.0 and circular economy journeys, ultimately achieving greater integration and success in both domains.

5 DISCUSSION

This chapter examines the integration of digital technologies to facilitate the transition to a circular economy within the manufacturing industry. By synthesizing findings from the literature review and case studies, the chapter addresses three primary research questions. First, it investigates the adoption of circular strategies with a focus on value retention processes. Second, it discusses the challenges associated with the implementation of Industry 4.0 technologies. Finally, the chapter explores how these technologies are employed to achieve a circular economy transition and presents a framework to elucidate the enabling role of digital technologies in realizing circular economy benefits.

5.1 Circular economy strategies adoption

In the context of circular economy strategies, the organisations studied typically implement a variety of circular economy strategies instead of focusing on a single approach. The most commonly employed strategies are repair, refurbish, reuse, reduce, remanufacture, and recycle. The selected sample places a clear emphasis on strategies for VRPs, meeting one of the requirements of this study.

The literature shows that the sample differs from the prevailing trend in most CE initiatives. These initiatives tend to prioritize recycling over VRP strategies. As a result, most CE initiatives in the current production system focus on incrementally optimizing resource use rather than addressing the overall extended use of resources.

Furthermore, the adoption rates of the 9R framework were compared for four case study groups. The pilot case achieved the highest level of circularity, followed by the furniture sector, then electronics and ICT. Finally, the household appliances group has the lowest level of circularity. The sample prefers the repair strategy over refurbishment, reuse, and remanufacture for adopting VRP strategies. Additionally, manufacturing companies tend to adopt multiple VRPs simultaneously rather than just one. The pilot case achieves the highest level of circularity, followed by furniture, electronics, and household appliances, similar to 9R implementation.

5.2 Challenges associated to circular economy transition

While the literature acknowledges the transformative potential of Industry 4.0 for circular businesses, this study's findings reveal significant roadblocks to its widespread adoption. The identified challenges in the case studies directly mirror the implementation barriers observed in the literature review. The limited scalability of circular models coupled with the novelty of I4.0 creates uncertainty, hindering broader application of these technologies. Moreover,the lack of awareness around I4.0 translates into companies struggling to define clear implementation roadmaps.

Furthermore, the skills gap identified in the literature is reflected in the case studies as a lack of digital expertise, which impedes effective implementation across the supply chain. Finally, the observation of outdated infrastructure in some companies aligns with the literature's recognition of infrastructure limitations as a hurdle for I4.0 adoption. By bridging this gap between theory and practice, this research offers valuable insights for companies seeking to integrate I4.0 within their circular business models.

As proposed by the literature, the challenges associated with implementing I4.0 can be effectively addressed through the development of a robust delivery system (BAG et al., 2018). This system extends beyond the mere acquisition of technology; it encompasses a comprehensive economic and social approach that fosters successful I4.0 adoption and positive outcomes in manufacturing operations.

The case studies provide compelling evidence for this approach. The case studies of companies such as ELECTRO5 and PILOT, which have been identified as advanced adopters of I4.0, demonstrate the efficacy of a well-designed delivery system. As highlighted in the literature, a key component of such a system is fostering a culture of learning through collaborative networks with suppliers, research institutes, and universities (BAG et al., 2018). This collaborative environment facilitates knowledge transfer and development, which is likely to have played a significant role in the success of ELECTRO5 and PILOT's I4.0 implementation.

5.3 Enabling circular economy through digital technologies

Prior research acknowledges the potential of I4.0 for circular businesses, but existing studies often focus on high-level connections or lack empirical data (DUBEY et al., 2019). This research addresses these gaps. Firstly, it explores companies' perspectives on implementing I4.0 technologies within their 9R circular strategies, fulfilling a previously acknowledged knowledge shortage (DUBEY et al., 2019). Secondly, it delves into a detailed analysis of how specific I4.0 technologies can support each aspect of the 9R framework, with a particular focus on strategies that extend product lifespans (reuse, repair, refurbishment, remanufacturing) (LASKURAIN-ITURBE et al., 2021).

By providing empirical evidence and a granular examination of I4.0's role within each 9R principle, this research aims to bridge the knowledge gap and offer practical insights for companies pursuing a more circular future. The literature review highlights that the reuse strategy is strongly supported by traceability technologies, such as RFID and BIM, while the repair strategy benefits from traceability technologies like blockchain. Additionally, repair is facilitated by virtualization technologies, including AI and digital twins, as well as by automation technologies like intelligent robots and flexibility technologies such as additive manufacturing and 3D printing. Refurbishment and remanufacturing strategies are closely linked with base technologies such as IoT, big data analytics, and cloud computing. Moreover, remanufacturing is further enabled by smart working technologies, including virtual reality and augmented reality.

Regaring the empirical studies results, the empirical study indicates that cloud computing and analytics were the most widely adopted technologies for base technology adoption, followed by big data. IoT was the least adopted technology. The analysed sample partially follows the pattern identified by Frank, Dalenogare e Ayala (2019), who suggests a rising complexity level when implementing foundational technologies in the following order: cloud computing, IoT, big data and analytics.

In relation to Smart Manufacturing technologies, the pilot case has implemented a wide range of tools including blockchain, RFID, AGVs and AI. This suggests that advanced adopters typically utilise all available technologies rather than just a select few. This shows that increasing maturity in I4.0 adoption requires the aggregation of many different technologies, rather than substituting one technology for another.

When analysing the adoption of Smart Manufacturing technologies in the furniture sector, it becomes evident that the industry has embraced vertical integration, flexibility, and traceability tools. Furthermore, the furniture industry is actively seeking technologies that enable the traceability of its products. In one of the case studies, a digital worker assistance system for inspection was identified as a potentially valuable technology for automating the quality assessment of the remanufacturing process, with future benefits.

The electronics industry has already employed vertical integration technologies. One case study has expressed interest in virtualisation technologies, such as AI and digital working assistance, for inspection. Blockchain has been identified as a traceability tool worth researching and investing in. However, there has been resistance to the adoption of Industry 4.0 technologies. Interviewees expressed fears regarding job loss opportunities, and some even commented on the lack of reliability of AI.

The household appliances group has not yet implemented Smart Manufacturing technologies in the CE context. However, one interviewee expressed interest in traceability technologies. The lower adoption of I4.0 may be since most CE initiatives are classified as incremental innovations that do not require many digital technologies due to their low implementation complexity. However, the household appliances sector stands out in terms of Smart Supply Chain technology adoption. This is because servitization business models require digital platforms that allow customers to obtain useful data from product usage.

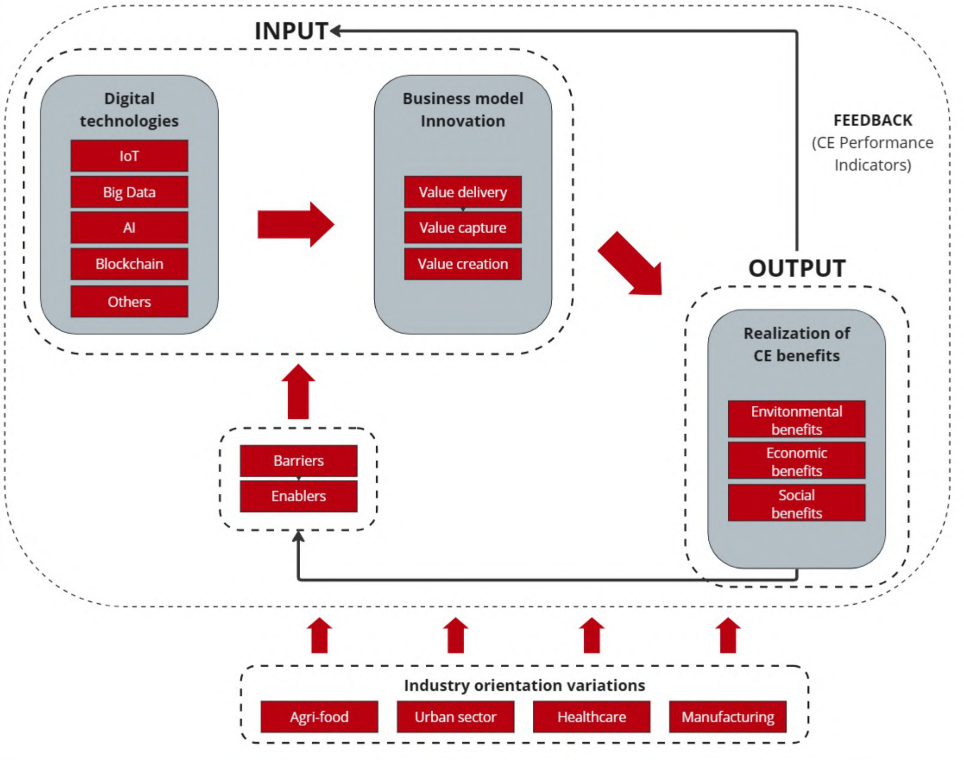
Therefore, implementing higher-level base technologies and smart manufacturing can lead to a greater implementation of circular economy principles, indicating that I4.0 is a strong enabler for circular economy transition. Furthermore, the use of base technologies can facilitate the implementation of smart manufacturing technologies.

This study builds upon the established link between Industry 4.0 technologies and their role in enabling the circular economy transition (CHAUHAN; SHARMA; SINGH, 2021). The empirical findings provide robust evidence to reinforce this positive relationship. The developed CE Maturity and I4.0 Readiness matrix serves as a powerful tool, demonstrating a clear correlation: firms with greater investments in I4.0 technologies tend to achieve significantly higher levels of CE maturity. However, the distribution of case studies within the matrix reveals a crucial insight. While a correlation exists, achieving significant progress towards both high CE maturity and high I4.0 readiness necessitates a more transformative approach. It is evident that incremental improvements are not sufficient to achieve the desired outcomes. Therefore, there is a clear need for a more fundamental shift in practices and strategies.

5.4 Framework for transitioning towards CE

This section aims to assess the enabling role of digitalisation in the CE transition using the framework developed by Chauhan, Parida e Dhir (2022). The paradigm shift from the linear economy to CE requires the contribution and commitment of stakeholders and the redesign of systems in line with the principles of business model innovation. Chauhan, Parida e Dhir (2022) introduces a framework (Figure 28) based on the Viable System Model (VSM) to guide organisations in the transition to a circular economy. This framework provides a comprehensive view of the aspects of the CE transition that need attention, drawing on current literature and emphasising the interconnectedness of these issues.

Figure 28: VSM-based framework for transition towards the CE



Source: Adapted from: Chauhan, Parida e Dhir (2022)

The interdisciplinary themes include digitalisation technologies and CE, barriers to digitalisation-led CE, enablers of digitalisation-led CE, digitalisation-led business model innovation and sector-specific studies. Rooted in systems thinking, VSM asserts that systems should remain viable even in turbulent environments and aims to ensure effective system functioning. It views systems as partially open, with dynamic interactions between components, and focuses on the systemic functioning of entities and actors. This framework places a company's primary activities, which are responsible for its products or services and reflect its identity, at the centre of the VSM (CHAUHAN; PARIDA; DHIR, 2022).

Figure 28 illustrates the enabling technologies and new business models that serve as inputs to the realization of CE benefits. Digitalisation can yield CE benefits in three distinct ways. Firstly, it significantly reinforces the circular economy by reinforcing enablers such as remanufacturing and ecosystem collaboration. Digital platforms facilitate seamless integration among partners, rendering them an optimal means of systematically driving CE, particularly in the management of resources beyond direct ownership or control.

The empirical component of this study also underscores the critical importance of digitalisation in achieving CE by improving ecosystem collaboration. This is evidenced by the following quotation from the PILOT case, which exemplifies the enabling role of Industry 4.0 in attaining CE:

> "*I think the role of I4.0 in attaining CE is an enabling role. Of course, a company can practice circular economy through manufacturing without I4.0. However, the crucial question is how profitable and sustainable it can be for the company in the long run. So, I believe that all the technologies I mentioned are vital for designing circular business models. They enable the sharing of information among partners, making collaboration easier and more effective.*"

Similarly, the ELECTRO5 case study highlights the transformative impact of digitalisation on stakeholder collaboration:

> "*Logistics, in particular, exemplifies the transformative power of digitisation. Previously, our processes relied on cumbersome methods like Excel spreadsheets and email communications, leading to inefficiencies. However, by implementing a collaborative cloud-based system, we streamlined communication and decision-making processes among stakeholders, resulting in faster and more cost-effective solutions.*"

Secondly, advanced technologies effectively address barriers to CE, such as market apathy, data scarcity, and cost issues. These companies adopt a customer-centric approach, enhance their internal data management, and reduce their operational costs by optimising the utilisation of resources and extending the product lifecycle. Consequently, the process of digitalisation enables companies to achieve both economic and environmental benefits.

The ELECTRO5 case study exemplifies the transformative potential of digital technologies in overcoming challenges associated with transitioning to a CE business model. By focusing on customer-centric solutions and leveraging advanced technologies, ELECTRO5 demonstrates how digitalization can effectively facilitate the transition to a circular economy. As articulated in the case study, technological innovation is crucial for surmounting existing barriers and advancing toward a more sustainable future:

> *"It is my firm conviction that technology represents the key to overcoming cost barriers, a pivotal factor in advancing sustainable practices. In pursuit of disruptive technologies, I recently proposed to a partner university the creation of a consumer-oriented system. This system would leverage cameras and apps to provide personalized recommendations for optimal device usage and disposal methods. By addressing individual needs and contexts, such technologies have the potential to mitigate the cost barriers that currently exist and to drive increased adoption rates. As volume increases, scalability and efficiency improvements follow, bolstered by enhanced competition and streamlined processes. Furthermore, material identification poses a significant challenge, particularly with plastics. To tackle this issue, we have explored advanced techniques such as artificial intelligence and hyperspectral imaging. Through ongoing research and innovation, we aim to overcome these challenges and pave the way for a brighter, more sustainable future."*

Thirdly, manufacturing firms can create, distribute, and capture value by addressing all facets of circular business models. For example, the advent of technologies such as the IoT and big data has opened up new avenues for firms to expand their service portfolios, thereby enhancing their ability to deliver value to customers. Furthermore, the utilisation of digital technologies confers social advantages, including enhanced workplace safety and reduced workplace hazards through automation (CHAUHAN; PARIDA; DHIR, 2022).

The realisation of CE benefits is also affected by business model innovation, which creates opportunities for value creation, capture, and delivery driven by the adoption of digitalisation technologies. Industry-specific variations impact digitalisation's type, extent, and the nature of business model innovation, influencing barriers and enablers, thereby affecting realised benefits. The empirical investigation conducted in this study delves into three distinct industry sectors – electronics and ICT, household appliances, and the furniture industry – alongside a case study within a university learning factory. Across these sectors, a comprehensive analysis unearthed various barriers and enablers shaping the implementation of Industry 4.0 technologies and subsequent realization of CE benefits.

In the electronics and ICT industry, companies are confronted with the rapid pace of technological change, shorter product life cycles, and the complexity of managing heterogeneous goods across distributed locations. These challenges necessitate the development of robust remanufacturing and lifecycle management capabilities. Although Industry 4.0 technologies such as the IoT, cloud computing, and cyber-physical systems are perceived as potential enablers, their wider implementation is hindered by a number of obstacles. The lack of top management commitment, reluctance to share proprietary product designs to protect intellectual property, and the absence of standards for lifecycle management represent key barriers to the wider implementation of Industry 4.0 technologies. Furthermore, there is a notable lack of comprehensive knowledge about the entire product lifecycle, which necessitates the development of user-friendly systems to engage stakeholders with limited experience. Despite the acknowledged value of technologies such as cloud computing and big data, concerns about job displacement and the reliability of advanced tools such as AI and blockchain persist, impeding their adoption.

The household appliances industry presents a scenario where there is hesitation to fully embrace digital technologies despite their clear benefits in supporting CE models such as servitization. The industry currently relies on base technologies like IoT for data collection, big data for analyzing customer behavior, and cloud computing for facilitating appliance sharing. However, the adoption of these technologies is often limited due to a lack of in-depth knowledge within the organizations. Many companies prefer incremental improvements over radical changes, leading to a cautious approach to the adoption of disruptive digital solutions and smart manufacturing technologies. This incremental adoption pattern, which focuses on extending product life and improving energy efficiency, is predominant among original equipment manufacturers, while more radical business models, supported by IoT and big data, are mainly driven by start-ups or external initiatives of large companies.

In the furniture industry, there is a growing interest in leveraging digital technologies to enhance operational efficiency and support sustainable practices. Technologies such as cloud computing, big data, and RFID are being explored for their potential to facilitate CE processes. However, significant barriers remain. The industry relies heavily on manual labour for processing reclaimed goods, and there is a pressing need for detailed information at every stage of the product lifecycle to achieve effective traceability and quality management. The lack of sufficient knowledge and skills for handling diverse materials and the individual assessment required for each returned item pose additional challenges. Furthermore, while there is interest in technologies that could automate quality assessments and enhance traceability, integrating these tools into the largely manual operations of the sector remains a significant challenge. In order to overcome these barriers and fully embrace the potential of Industry 4.0 technologies, it is crucial for the sector to enhance sustainability awareness and to engage in continuous learning.

Finally, the PILOT case serves as a benchmark for advanced Industry 4.0 adoption, illustrating how comprehensive integration across various technology groups can be achieved. This case highlights the successful implementation of IoT, cloud computing, AI, robotics, and advanced traceability tools such as blockchain and RFID. The high level of adoption in the PILOT case is supported by a robust delivery system and a collaborative network that promotes knowledge transfer and development. This case study serves to illustrate the importance of adopting a wide array of technologies in order to achieve greater maturity in the implementation of Industry 4.0. This, in turn, will help to overcome the barriers that other sectors face. It demonstrates that continuous innovation and coordinated efforts are essential for the realisation of the full potential of digitalisation in advancing towards a circular economy.

In summary, each sector faces unique challenges and barriers in the implementation of Industry 4.0 technologies to achieve CE benefits. The electronics and ICT industry struggles with intellectual property concerns and lifecycle knowledge gaps. The household appliances sector is hindered by a preference for incremental innovation and a lack of digital integration knowledge. The furniture industry faces difficulties in integrating digital tools into manual operations and managing diverse reclaimed materials. The PILOT case provides a blueprint for overcoming these barriers through comprehensive technological adoption and collaborative innovation. Addressing these sector-specific challenges is crucial for enabling the broader adoption of digital technologies and achieving the transformative benefits of a circular economy.

The viability of the system in the context of circular economy is subject to variations in industry orientation, influencing the extent and nature of digitalisation, business model innovation, as well as the barriers and enablers encountered. This investigation into system viability intertwines the realization of CE benefits with a feedback loop based on CE indicators. The complex behavior of the system, amid industry orientation variations, is assessed and refined through feedback loops, ensuring that any change affects all components of the system. Extracting key parameters from the literature, such as barriers and enablers, through the present SLR study contributes to this process (CHAUHAN;

PARIDA; DHIR, 2022).

Business model innovation, described as a means through which firms create value, is pivotal in driving circular business model innovation system-wide, facilitated by digitalisation. The sustainability of a viable CE system relies on appropriate technologies and enablers, reinforced by feedback loops. These loops guide actors in making necessary adjustments to enhance system performance. A multi-sectoral system is deemed viable when it maintains balance in feedback cycles, adapts to changes, and rectifies any adverse performance. The Viable System Model underscores collaborative actions, incorporating stakeholders' perspectives, to achieve CE goals through the feedback loop (CHAUHAN; PARIDA; DHIR, 2022).

Policymakers strive for the appropriate policy mix, while managers, informed by CE performance indicators, adjust CBMs or digitalisation strategies accordingly. Consistent with the VSM, the system evolves over time, learning and progressing. Involving stakeholders in CE endeavors holds significant value, fostering new CBM opportunities. In line with this approach, the feedback loop emphasizes decision-making and actions necessary for achieving CE goals. The VSM-based framework sheds light on the dynamics of multi-sectoral systems, emphasizing the need for adjustments and streamlining in response to changing environments. This framework enables constructive dialogue on feasible policy interventions and expected strategic outcomes (CHAUHAN; PARIDA; DHIR, 2022).

6 CONCLUSION AND OUTLOOK

This study investigates the implementation of essential circular economy strategies in the manufacturing industry and the role of Industry 4.0 technologies in addressing the challenges associated with this transition. The findings are discussed in relation to the three research questions posed, providing a comprehensive understanding of the interactions between CE and I4.0.

Firstly, the research sought to answer how CE concepts, specifically reuse, repair, refurbish and remanufacture, are implemented in the manufacturing industry. Empirical evidence indicates that organisations tend to implement a variety of circular economy strategies rather than concentrating on a single approach. The selected sample places a clear emphasis on strategies for value retention processes, which meet one of the requirements of this study. This preference for VRPs signals a strategic shift towards practices that retain more value from products and materials, emphasising repair, refurbishment, and reuse over processes like recycling, which typically come into play at the end of a product's life cycle.

In contrast to the prevailing trends in the literature, which often prioritize recycling over Value Retention Process, the selected sample presents a notable departure from this pattern (MORSELETTO, 2020). While the literature indicates that the majority of CE initiatives in the current production system focus on incrementally optimizing resource use rather than considering the extended use of resource, the strategies evident in the case studies reflect a deeper commitment to extending product lifecycles and maximizing resource utilization. Among the strategies commonly adopted in the case studies are repair, refurbishment, reuse, reduce, remanufacture, and recycling, with a clear preference evident for VRPs.

The investigation further highlights the diverse landscape of CE adoption within the manufacturing sector, with some companies demonstrating advanced integration of CE principles while others are in the early stages of adoption. Firms like ELECTRO1 and PILOT showcase robust strategies that extend product lifecycles and uphold value retention through extensive reuse, repair, refurbishment, and remanufacture activities, showcasing the operational and environmental benefits of systematic CE integration. Conversely, companies like HOUSE2 and ELECTRO2 show sporadic implementation hindered by resource limitations and strategic prioritization challenges. This discrepancy underscores the phased nature of CE maturity within the industry, influenced by both internal capacities and external pressures, and reflects varying degrees of commitment and capability across different companies.

Secondly, in exploring the primary challenges that the manufacturing industry faces when transitioning to a circular model, the research revealed several significant obstacles. The main challenge faced by organisations when employing circular economy strategies is related to product characteristics and process challenges, such as a lack of knowledge and expertise in circular practices and high product complexity due to the new procedures and tools required. The second most occurring challenge is the lack of standards and regulations, followed by supply chain management challenges due to uncertainty of return flows, lack of transport and infrastructure, and difficulty in finding suitable supply chain partners.

Additionally, the organisations face technology-related challenges, including the inability to keep up with constant technological improvements and concerns regarding the data security of returned devices. Proving to the top management team that circular initiatives can be economically viable can be difficult. Additionally, companies implementing CE initiatives face challenges with user behaviour as customers often prefer to buy brand new devices due to the common perception that second-hand products are inferior to new ones. Some organisations may face resistance to implementing CE initiatives due to a dominant linear cultural mindset, which can be difficult to change.

The study elucidates the varied challenges encountered by manufacturing firms at different stages of circular economy adoption, illustrating the contrasting positions of advanced adopters like ELECTRO5 and ELECTRO1 and novice participants like HOUSE2 and ELECTRO2. While advanced adopters grapple with integrating circular practices into established frameworks while ensuring competitiveness, early-stage participants face foundational hurdles such as technology gaps and a lack of managerial support. Despite these differences, all firms share a common imperative: investing in technology to overcome barriers and in employee training to deepen their understanding of circular economy principles. These investments are essential for fostering innovation and sustainability, key components for a successful transition to a circular economy model.

Thirdly, to address the third research question of this thesis, the intricate relationship between Industry 4.0 technologies and the essential transition to a circular economy is examined. From both theoretical and empirical perspectives, CE and I4.0 are increasingly important among scholars and practitioners due to their potential to enhance sustainable production and operational efficiency. I4.0 front-end technologies, including Smart Manufacturing, Smart Products, Smart Supply Chains, and Smart Working, along with base technologies such as IoT, cloud computing, big data, and analytics, significantly enhance supply chain visibility and address issues related to low responsiveness and high uncertainty (BAG et al., 2018). Empirical data shows cloud computing and analytics as the most widely adopted technologies, followed by big data, with IoT being the least adopted. This pattern aligns partially with rising complexity model for implementing base technologies developed by Frank, Dalenogare e Ayala (2019).

Moreover the case studies sample reveal a clear correlation between higher investments in I4.0 technologies and greater CE maturity. Organizations that invest more in these advanced technologies achieve higher levels of circularity. However, significant progress in CE requires transformative changes rather than incremental improvements, necessitating a radical overhaul of business processes and strategies.

The investigation into the integration of I4.0 technologies with CE principles presents significant theoretical implications. Firstly, the thesis validates the proposition that higher investments in I4.0 technologies correlate with greater CE maturity, reinforcing the importance of technological advancements in enhancing sustainable production and operational efficiency. Additionally, the utilization of a comprehensive framework based on the Viable System Model from Chauhan, Parida e Dhir (2022) underscores the critical role of digital technologies in overcoming traditional CE challenges, such as market apathy and high costs. This framework provides a theoretical foundation for understanding how organizations can transition towards circular business models. Moreover, the emphasis on system redesign and stakeholder commitment aligns with theories that advocate for holistic approaches in sustainable development. Transformative changes that include strategic technology investments, rather than incremental improvements, are essential for realizing substantial CE benefits.

The practical implications of incorporating I4.0 technologies into circular economy practices are significant. Leveraging these technologies allows organizations to achieve greater efficiency, reduce waste, and create more sustainable business models. Case studies of firms like PILOT and ELECTRO5 illustrate how this integration can lead to improved economic performance and resource efficiency, serving as benchmarks for other organizations aiming to enhance their CE maturity through digital transformation. The correlation analysis in the thesis suggests that firms with higher maturity levels in both CE and I4.0 are more likely to adopt a comprehensive range of advanced technologies and strategies. This insight can inform strategic planning and help firms align their technological and sustainability efforts more effectively. The assessment of the CE Maturity and I4.0 Readiness developed in the study reveals a clear correlation between higher investments in Industry 4.0 technologies and greater CE maturity. Organisations that invest more in these advanced technologies tend to achieve higher levels of circularity. However, the matrix also indicates that achieving significant progress in CE requires transformative changes rather than incremental improvements. Incremental changes often result in limited gains, whereas a more radical overhaul of business processes and strategies is necessary to fully realise the benefits of a circular economy.

Despite these promising findings, the study has several limitations. The sample size of stakeholders in the empirical study is relatively small, with only ten interviews conducted. This limits the generalizability of the findings and suggests the need for further validation with a larger sample. Additionally, the empirical study was unable to identify specific I4.0 technologies for each value retention process due to data limitations. This highlights a gap in current research and points to a need for more detailed studies on the application of these technologies in specific CE strategies.

To address these limitations, future research should expand the sample size to include a larger and more diverse group of stakeholders, enhancing the generalizability of the findings. Detailed technological analysis is necessary to identify specific I4.0 technologies that address value retention process implementation challenges. Further studies should focus on more granular analyses of how these technologies support each aspect of circular strategies. Research should also explore strategies for bridging the digital skills gap, including comprehensive training programs and collaborative networks with suppliers, research institutes, and universities. Understanding sector-specific challenges and opportunities in adopting CE and I4.0 practices can help tailor strategies for different industries, involving the development of industry-specific frameworks and best practices. Lastly, conducting longitudinal studies to observe the long-term effects of integrating I4.0 technologies with CE strategies can provide deeper insights into their sustainability and economic impacts.

In conclusion, while the integration of Industry 4.0 technologies with circular economy strategies presents substantial theoretical and practical benefits, addressing the identified limitations and pursuing the suggested avenues for future research will be crucial in advancing this field.

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APPENDIX A – RESEARCH PROTOCOL

The following research protocol was established, to facilitate the qualitative data collection during interviews. To keep critical information confidential, a simplified version is here.

Phase 0: Presentation and introduction of the theme

- **Presentation:** Good morning, my name is Beatriz, and I am a student from Technische Universität Darmstadt and Universidade de São Paulo. I want to thank you for agreeing to undertake the interview.
- **Aim:** The aim of this interview is to investigate the adoption of four major concepts of circular economy (repair, reuse, refurbishment, and remanufacturing) in the industry and the identification of technologies to overcome challenges in the implementation of the concepts.
- **Support material:** I shared with you some supporting documentation, including circular strategies and Industry 4.0 technologies. I hope you have had time to read it.
- **General Instruction** Please be aware that there is no right or wrong answer, but I hope you answer based on your best knowledge.
- **Confidentiality:** No information about the company name will be revealed. The interview will be transcribed, to extract the most relevant parts from your valuable feedback. Data will be treated in a confidential way.

Phase 1: General questions about the company

First, I would like to ask you some general questions about your company. Could you please briefly describe:

- the main activities of your company;

- the size of the company (i.e. the number of employees);
- your role in the company;
- if a CE project is carried out by your company;
  - if yes, the scope of the CE project;
  - if yes, the motivation behind the decision to undertake such a project.

Phase 2: Questions about the CE projects carried out

Now I have some questions regarding the adoption of CE strategies in your company.

- First how would you classify the adoption of CE in your company?
  - Not adopted
  - Starting to consider adoption
  - Planning adoption
  - Adopted
  - Fully adopted
- How important is circular manufacturing for your company when compared with other competitive manufacturing capabilities?
  - Very important
  - Important
  - Neutral
  - Low importance
  - Not at all important
- According to the information provided in the support material, could you please classify which of the following CE strategies your company adopts and how these concepts have been implemented by the company?
  - Refuse
  - Rethink
  - Reduce
  - Reuse

  - Repair
  - Refurbish
  - Remanufacture
  - Repurpose
  - Recycle
  - Recover
  - Sharing systems
  - Servitizations (PSS)
  - Others

Phase 3: Specific questions about CE challenges (Skip if no CE project)

Now I would like to discuss the implementation of the CE project.

- What were the challenges faced in the implementation and how did your company try to overcome them?
- Based on your experience, what core capabilities were required in manufacturing processes, systems, supply chains, services, managerial practices to enable a transition to circular manufacturing business models? And how can these be developed?
- What were the key benefits?
- What was the role of digitalisation in the CE project?

Phase 4: Enabling technologies investigation

Now I have some questions about the Industry 4.0 technologies.

- First how would you classify the adoption of Industry 4.0 technologies in your company?
  - Not adopted
  - Starting to consider adoption
  - Planning adoption
  - Adopted
  - Fully adopted

- Which of the following base technologies does your company use?
  - Internet of Things (IoT)
  - Cloud Computing
  - Big Data
  - Analytics
  - None of the above
- Which technologies of Smart Manufacturing does your company use?
- What was the main purpose in adopting these technologies?
  - Vertical integration
  - Virtualization
  - Automation
  - Traceability
  - Flexibility
  - Energy management
- Which product's capability was improved when adopting these technologies?
  - Product's connectivity
  - Product's monitoring
  - Product's control
  - Product's optimization
  - Product's autonomy
- Which of the following technologies for Smart Working does your company adopt?
  - Remote monitoring of production
  - Remote operation of production
  - Augmented reality for maintenance
  - Virtual reality for workers training
  - Augmented and virtual reality for product development
  - Collaborative robots

- Regarding technologies for Smart Supply Chain, does your company adopt any digital platforms with suppliers, customers, or other company units?
- *(If company doesn´t adopt many technologies) Why is the pace of digitalisation slow despite its role as a driver of CE?
- Are there any technologies that you are planning to implement in the future?

Phase 5: Final questions and conclusion

- Can you please describe how these technologies can be utilized to attain the CE?
- Lastly, what are the partners along the supply chain that help make the business viable?
- Could you name them and give me the contact so that you can map the ecosystem better.

Thank you again for your time. Results from your case are going to be systematized and finalized in an anonymous way. I will be glad to share the final report with you.

APPENDIX B – E-MAIL TEMPLATE

Subject: Master Thesis Research — Enabling technologies for Circular Economy

Body:

Dear Mr/Ms X,

My name is Beatriz Makssoudian Ferraz, and I am a Master student at Technische Universität Darmstadt and Universidade de São Paulo. Currently I am writing my Master Thesis entitled "Enabling technologies for circular economy transition in the manufacturing industry".

The goal of my study is to investigate the adoption four major concepts of circular economy (repair, reuse, refurbishment, and remanufacturing) in the industry and the identification of technologies that can help overcome the challenges in the implementation of the concepts. Therefore, I am conducting an empirical study among companies that fulfil these requirements and it would be highly appreciated if Company X took part in this study.

Would you have availability and interest in taking part in this research? For more information, kindly find attached a detailed briefing of the study. If you have further questions, please don´t hesitate to contact me.

Sincerely,

Beatriz Makssoudian Ferraz

APPENDIX C – BRIEFING

Briefing - Enabling technologies for circular economy transition in the manufacturing industry

Circular economy has become a strategic and sustainable economic model that distances itself from the current linear model of extraction, transformation, use and disposal, through a system that is restorative or regenerative by design. Many industries from the manufacturing sector are already creating additional value by adopting circular economy practices. However, the increasing implementation of circular economy concepts has brought challenges related to the need of new competencies. New technologies from Industry 4.0 can potentially support the mitigation of problems associated with the transition toward a more circular economy.

Therefore, this work aims to investigate the adoption of four major concepts of circular economy in the manufacturing industry through literature review and expert interviews. The study enables the recognition of competencies required to implement the four processes, the analysis of related implementation problems, and the identification of technologies used by the industry that can help overcome the challenges.

This work is part of a master's thesis defended within the partnership between the Universidade de São Paulo (Brazil) and the Technische Universität Darmstadt (Germany) in the Double Degree Program.