The impact of Industry 4.0 technologies on Circular Economy adoption: the case of the Finnish packaging industry

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ABSTRACT

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This thesis undertakes a comprehensive examination of Industry 4.0 technologies, specifically exploring their potential applications within the plastic packaging industry, with an emphasis on advancing traceability and transparency along the value chain.
The study employs a qualitative methodology, including a systematic review of the expanding literature on Circular Economy (CE) considerations in plastics, along with the evolving role of emerging Industry 4.0 technologies. In parallel, qualitative insights are gathered from industry experts through semi-structured interviews, providing valuable practical input to the research.
The analysis reveals key insights, shedding light on the transformative impact Industry 4.0 can have in promoting CE practices within an industry facing substantial challenges. Expert testimony not only highlights the potential benefits, but also articulates the challenges inherent in this paradigm shift, outlining a trajectory toward a more sustainable future.
The plastics industry is currently witnessing a convergence of innovation and environmental responsibility that instills a sense of optimism. Industry 4.0, far from merely addressing existing challenges, promotes a collaborative ecosystem in which stakeholders collectively strive to achieve a shared goal.
This technological shift, which goes beyond a transitory industry trend, signifies a collective dedication to a future in which economic prosperity aligns perfectly with sustainability.
The plastics industry stands at the threshold of an era in which Industry 4.0 transcends its designation as a mere buzzword, evolving into a guiding principle for achieving circularity. The implementation of these technologies goes beyond corporate strategy and represents a commitment to practices that transcend corporate boundaries. In essence, this research not only advances the theoretical understanding of the field, but also provides practical implications for organizations that aspire to promote circular and transparent behaviors within their operations.

SYMBOLS AND ABBREVIATIONS

(CE) Circular Economy

(CPS) Cyber-Physical Systems

(PCW) Post-Consumer Plastic Waste

(VC) Value Chain

(SC) Supply Chain

(GHG) Greenhouse Gas Emissions

(EPR) Extended Producer Responsibility

(PP) Polypropylene

(PS) Polystyrene

(PVC) Polyvinylchloride

(PE) Polyethylene

(PET) Polyethylene Terephthalate

(HDPE) High Density Polyethylene

(IoT) Internet of Things

(AI) Artificial Intelligence

(RFID) Radio-Frequency Identification

(ICT) Information and Communication Technology

(MCPs) Materials, Components, and Products

(KPI) Key Performance Indicator

Table of Contents

1 Introduction 1

1.1 Background of the study 2

1.2 Research method 5

1.3 Research gap and research questions 5

1.4 Research boundaries 6

2 Plastics and the Circular Economy 8

2.1 Plastics and their environmental impact 8

2.2 Packaging 8

2.3 Plastic packaging 10

2.4 Plastic value chain 13

2.4.1 Design 13

2.4.2 Production 14

2.4.3 Use 15

2.4.4 End-of-Life 16

2.5 From the linear economy to the circular economy 16

2.6 Circular Economy: etymology and definitions 18

2.6.1 Chosen definition 19

2.7 European regulatory framework on the circular economy 21

2.8 Plastic recycling 24

2.8.1 Mechanical recycling 25

2.8.2 Chemical recycling 25

2.8.3 Incineration 26

3 Industry 4.0 and Circular Economy 28

3.1 From industry 1.0 to industry 4.0 28

3.2 Industry 4.0 definitions and enabling technologies 29

3.3 Industry 4.0 and circular economy 31

3.4 Definition of traceability 34

3.4.1 Traceability in supply chain 35

3.4.2 Industry 4.0 tracking systems in the agri-food sector 37

3.4.3 Enabling technologies 38

3.4.3.1 Blockchain technology 39

3.4.3.2 Internet of things 42

3.4.3.3 Artificial Intelligence 44

4 Research Design and Methods 47

4.1 Research strategy 47

4.2 Interviews data collection 48
4.2.1 Data analysis 50
4.3 Results 50
4.3.1 Integrated circular economy framework: plastic management and sustainable practices 51
4.3.2 Technological integration in plastic industry – current practices, challenges, and future directions 53
4.3.3 Enhancing supply chain dynamics – current practices and supply chain collaboration 54
4.3.4 EU regulations and ambitions in plastic and plastic packaging 56
4.3.5 Exploring the drivers to the change 57
4.3.6 Exploring the challenges to the change 58
4.3.7 IOT in Industry 4.0 - challenges, drivers in application and potential benefits 60
4.3.8 Blockchain in industry 4.0 - challenges, drivers in adoption and potential benefits 62
4.3.9 AI in industry 4.0 challenges, future prospects and potential benefits 63
5 Discussion and Conclusion 65
5.1 Discussion 65
5.2 Managerial and policy implications 72
5.3 Limitations and suggestions 73
5.4 Conclusions 74
References 76

Appendices

Appendix 1: Interview Protocol
Appendix 2: Codebook

Figures

Figure 1: The realm of the packaging industry
Figure 2: Applications of thermoplastic
Figure 3: Plastic value chain
Figure 4: Linear model “take, make, dispose”
Figure 5: CE from the point of view of the chosen definition
Figure 6: The four industrial revolutions
Figure 7: Impact of industry 4.0 on the plastic value chain stages by number of mentions
Figure 8: Representation of typical circular supply chain reverse processes
Figure 9: IOT architecture
Figure 10: Research strategy

Tables

Table 1: European Regulatory framework
Table 2: Plastic recycling process: Criticisms
Table 3: Industry 4.0 technologies
Table 4: Emerging technologies by number of mentions
Table 5: Details on interviewee profiles and interview duration

1 Introduction

Finland and the European Union (EU) are taking proactive measures to re-evaluate the classification of plastic as waste. This shift in approach has significant implications for the annual disposal of nearly 300,000 tons of plastic, calling for the creation of improved ways to raise the effectiveness and durability of products made of plastic. However, there is a rising opinion around the world that recycling plastic is still quite difficult, especially when compared to other raw materials like steel and wood. The value of recycled plastic is notably higher when it is in a clearer and less extensively used state, often referred to as "virgin" plastic. Stringent hygiene regulations imposed on the food packaging industry result in large quantities of the most valuable plastic being consumed in their daily operations. However, most actors within the industry exhibit a deficiency in possessing shared databases with their counterparts, as well as a dearth of understanding regarding the quantities of material being cycled and the dynamics of the market pertaining to high-grade recycled plastic. Consequently, a substantial portion of valuable materials is squandered, either remaining unrecycled or subjected to inefficient recycling processes, particularly in instances where the demand for superior quality is not imperative, such as in applications involving fillings. The linear model of plastic usage, characterized by a produce-use-dispose approach, gives rise to various issues such as material leakage into the environment and CO2 emissions from incineration (Rumetshofer & Fischer, 2023). Each year, coastal countries contribute an estimated 4.8 to 12.7 million tons of plastics entering the ocean (Jambeck et al., 2015). In 2020, 29.5 million tons of post-consumer plastic waste (PCW) were collected in Europe alone. Approximately 23.4% of this PCW stream was disposed of in landfills, 42.0% was burned, and 34.6% was recycled (Plastics Europe, 2021). The main reason for the large discrepancy of almost 25.5 million tons between the manufacturing of plastic and the collection of plastic garbage is that products have different lifespans, which leads to a build-up of plastic items. This collection demonstrates these items' potential as recycling feedstock in the future (Rumetshofer & Fischer, 2023).

The shift to a Circular Economy (CE), which, as the name implies, offers the economic system an alternate, cyclical flow pattern, is one recommended strategy to overcome the

issues with the linear economy of plastics (Korhonen et al., 2018). This shift aims to maintain materials within a closed loop system and decrease the reliance on fossil resources (The New Plastics Economy, 2017). This dissertation will also explore the intersection of Industry 4.0 with the aforementioned transition to a CE, delving into how Industry 4.0 can derive benefits from it.

Indeed, emerging technologies associated with the Industry 4.0 revolution have the potential to reshape traditional business practices and create value within a circular economic framework. This transformation allows for the disentanglement of economic growth from the depletion of natural resources, in line with the World Economic Forum's perspective (2017). According to Xu et al., (2018), Industry 4.0 essentially emphasizes complete digitalization and the integration of digital industrial ecosystems in order to achieve completely integrated solutions.

The key technologies that support Industry 4.0 are cloud computing, and big data analytics, as noted by Zhong et al. (2016), Hermann et al. (2016), and Xu et al. (2018). Cyber-physical systems (CPS) are also part of this foundation. Moreover, Industry 4.0 also includes state-of-the-art innovations as acknowledged by Boston Consulting Group (BCG, 2015), Bahrin et al. (2016), Rao & Prasad (2018), and others, like additive manufacturing, simulation, augmented reality, artificial intelligence (AI), autonomous robotics, and horizontal and vertical systems integration.

The thesis addresses concerns related to the move towards a CE for plastic in the food sector, focusing in particular on a key obstacle to achieving circularity in plastic recycling, namely the lack of information sharing between all participants in the value chain (VC) (Rumetshofer & Fischer, 2023). Consequently, the study focuses on Industry 4.0 technologies as catalysts for this transition.

1.1 Background of the study

Plastics are a broad category of materials with properties suitable for use in everything from food packaging to automotive applications. Without plastics, food loss and waste would be more likely to endanger sustainable development (Ögmundarson et al. 2022). Due to their unique mechanical properties, plastics have a wide range of applications; yet, when plastic trash is inadequately managed after disposal, problems arise (Barnes et al., 2009). According

to Geyer et al. (2017), just 9% of the plastic manufactured between 1950 and 2015 was recycled, 12% was burned, and the majority was disposed of in landfills and the environment. By keeping plastic materials in closed-loop systems, a CE for plastics has been hailed as a sustainable alternative to the present production-consumption models for addressing the crisis of plastic waste (Maione et al., 2022).

The current iteration of the CE is not the product of a single thinker, but rather combines ideas from multiple schools of thought that share the concept of closed loops (Ellen MacArthur Foundation, 2015). Of them, the idea of industrial ecology is the most relevant to our study and consistent with the notion of the CE that we have selected.

According to Erkman's (1997) report, industrial ecology was first introduced in the late 1980s. As stated by Lowe and Evans (1995), it is a comprehensive and all-encompassing framework intended to guide the industrial system's transition toward sustainability. The basic concept of industrial metabolism, first proposed by Robert U. Ayres (1988), plays a central role in industrial ecology, focusing on improving our understanding of how society uses natural resources and how those resources affect the environment as a whole (Anderberg, 1998).

Alongside this idea, the term industrial symbiosis (IS) takes on significant significance in the field of industrial ecology. The fundamental principle of IS is the creation of concrete links between independent businesses via the transfer of resources, energy, water, and waste products (Chertow, 2000). Prosman et al. (2017) emphasized that industrial symbiosis is a critical tactic for stopping material flows.

The trajectory of the global economy has been mostly determined by a linear production model, even despite the advances in sustainable development and industrial ecology. Consumer items are produced from raw resources, sold, used, and then disposed of as garbage under this linear paradigm (Saavedra et al. 2017).

CE therefore is gaining significant global acceptance. Governments all around the world have accepted its central notion of switching from the present linear "take-make-use-dispose" economy to one that is restorative and regenerative by design (Ellen MacArthur Foundation, 2015). Plastic waste recycling has advanced in order to apply the CE, with the aim of reusing plastic waste into new material and bringing it back into the system as a new product (Hahladakis & Iacovidou, 2019).

There is now an abundance of definitions to describe CE. For the purposes of this thesis, because of its ability to provide a comprehensive perspective on the CE, addressing various

dimensions such as environmental, technical, social, and economic aspects, the definition of this concept will be that the CE is "a system that has the ability to restore, retain and redistribute materials, components and products (MCPs) in the best possible way and for as long as it is environmentally, technically, socially and economically feasible" (Hahladakis & Iacovidou, 2019). The method of implementation is not one size fits all. Because of this, in order to implement the CE, both national and local governments must create their own frameworks and policies that take into account organizational structures, systems of governance, and regional variations. The system might need to be completely redesigned in certain situations (Hahladakis & Iacovidou, 2019). This comprehensive approach facilitates a deeper and more holistic exploration of the concept within the thesis.

Transitioning from linear globalized economies, which prioritize fast and cheap production and distribution of goods, to circular economies that emphasize efficient resource utilization and environmental restoration, necessitates substantial transformations across various societal domains. These changes encompass expectations, practices, regulations, and technologies (Capetillo et al., 2022).

The absence of efficient and consistent traceability along VCs poses a significant obstacle to enhancing the management of plastics across supply chains (SC) (Bishop et al., 2022; White Paper Plastics, the Circular Economy and Global Trade, 2020). The capacity to trace plastics has been hindered by several factors, such as the comparative ease of deidentifying plastics in contrast to materials like timber, the extensive production of plastics, and the diverse range of material properties inherent to plastics. These factors contribute to the extensive incorporation of plastics in numerous applications that generate waste. Fortunately, there has been notable progress in enhancing the technical capability to trace plastics in recent years (Johnson et al., 2022).

In the context of this thesis, tracking is the systematic monitoring of data and materials from raw materials to finished goods and beyond (Rumetshofer & Fischer, 2023). While there is not a single technology that can be seen as a magic bullet for implementing circular economies, some new technologies provide bright opportunities for adopting more circular methods of resource usage and service delivery. There is a growing body of research examining both the inherent constraints and possible benefits of these developing technologies for circular economies. The advent of extensive digital technology intended for industrial use, commonly known as Industry 4.0, has been acknowledged as a critical enabler of various behaviors that are consistent with the objectives of the CE (Capetillo et al., 2022).

1.2 Research method

This thesis employed an exploratory, qualitative research approach to gather and analyze data. The research process began with a systematic literature review, which involved the study of relevant concepts to familiarize with the research area, identify research gaps, and formulate research questions. Various articles and scientific sources were reviewed in depth to understand existing studies related to the research topic. This literature review served as the basis for primary data collection.

The Web of Science Database available through the Lut Primo portal was used to search for scientific articles useful for the study. Boolean logic was made use of in the search for articles by specifically using "AND", "OR"; "NOT" to bind the most used search terms. These search terms include Supply Chain, Sustainable Supply Chain Management; Circular Economy; Plastic; Plastic Industry; Plastic Value; Plastic Tracking; Plastic Traceability; Plastic Value Chain; Industry 4.0; Industry 4.0 technologies; IoT; Blockchain; AI, etc.

After completing the literature review, primary data were collected to obtain new insights and empirical material from different perspectives in the field of research. Semi-structured interviews were conducted with experts, a tool considered suitable for data collection in exploratory and qualitative research when investigating novel topics. Primary data obtained from these interviews were collected and analyzed to enhance understanding of the research area.

The interviews were therefore recorded, transcribed, and then coded and themed using NVIVO Software. The approach followed in the coding and thematization of the interviews is called thematic analysis, which is used to create themes useful in answering the research questions.

Subsequently from the results obtained from the two research methodologies, a joint discussion was conducted to jointly present the outcomes of the thesis.

1.3 Research gap and research questions

Research indicates that there is a strong need to have a deeper understanding of how cutting-edge technology may support circular alternatives for the recycling and management of

plastic trash, as well as more sustainable solutions within VC (Bag et al., 2018; Nižetić et al., 2019).

This thesis endeavors to comprehend the significance of pivotal emerging technologies in the transition towards a CE within the plastics VC. The objective is to assess their potential impact and identify the barriers that hinder their adoption and diffusion. This is accomplished through a methodical review of pertinent research literature and semi-structured interviews.

Therefore, this paper aims to address a set of research questions and sub-questions, which we will thoroughly examine to offer comprehensive insights. The inquiries to be explored are as follows:

RQ1: What is the role of Industry 4.0 technologies in implementing Circular Economy principles in the plastics industry?

SQ1: What are the main drivers and barriers to the adoption and diffusion of Industry 4.0 to transition to a circular economy?

RQ2: What are the key Industry 4.0 technologies that can be leveraged to implement a plastic recycling tracking system and how can they be implemented?

The topics addressed in the presented research questions show limited application to date, in particular regarding the domain of plastic packaging.

This situation offers the opportunity to contribute to the existing body of research which, as noted above, is remarkably sparse. Furthermore, engaging in semi-structured interviews offers the prospect of direct interaction with professionals actively involved in the industry. Such efforts could prove instrumental not only in improving the current study, but also in gathering information for potential avenues of future research.

1.4 Research boundaries

This research project is subject to some limitations that define the scope and boundaries of the study. Firstly, the research mainly focuses on the implementation of a plastic packaging traceability system in the food service sector, using advanced Industry 4.0 technologies. It is

important to note that the findings and conclusions derived from this research have primary relevance in this specific context and may not be easily applicable to other countries or sectors. Changes in regulatory frameworks, infrastructure and industry practices could have a significant impact on the feasibility and suitability of the proposed tracking system.

Secondly, the research analyzes the challenges and drivers of the plastic and food packaging sector with the aim of highlighting possible solutions specific to this sector. Consequently, the data that will be highlighted could be subject to variations due to distinct dynamics depending on the specific sector of reference.

Furthermore, the project mainly studies how Industry 4.0 technologies could help simplify the implementation of the plastic packaging traceability system. This research focuses on examining the effectiveness and applicability of Industry 4.0 technologies in the specified context, although there may be other technological options. In this study, it is possible to dedicate a limited investigation to other possible solutions.

Importantly, this research does not include full implementation or a full evaluation of the tracking system. Overcoming specific implementation challenges or providing detailed technical solutions is beyond the scope of this research.

Finally, the research primarily considers the perspectives of stakeholders involved in the food service industry, including manufacturers, suppliers, and waste management agencies. While their perspectives are given due consideration, the perspectives of other relevant stakeholders, such as consumers or regulators, have not been comprehensively addressed in this study.

Recognizing these boundaries, the research maintains a focused approach, providing valuable insights into the development of an Industry 4.0-based tracking system for plastic recycling in the food service sector, respecting the boundaries and contextual considerations inherent to the scope of the research.

2 Plastics and the Circular Economy

2.1 Plastics and their environmental impact

Plastic is extensively utilized in our day-to-day activities, making it one of the most frequently employed materials (Eriksen et al., 2020). In the year 2019, approximately 50.7 million tons of plastic were consumed in Europe (PlasticsEurope, 2021). The versatility of plastic, characterized by its affordability, lightweight nature, malleability, and durability, contributes to its extensive utilization in various industrial processes, products, and packaging (Bishop et al., 2020; Heller et al., 2020).

Although the use of plastic in goods and packaging has many positive social and economic effects, there are environmental dangers associated with its broad use, including pollution and greenhouse gas emissions (GHG) (European Commission, 2018; Hahladakis et al., 2018). It is estimated that between 4.8 million and 12.7 million tons of plastic are lost into the environment annually (Jambeck et al., 2015), and in 2015 alone, emissions resulting from the incineration of plastic packaging amounted to approximately 16 million tons of CO2 equivalents (Hamilton and Feit, 2019).

2.2 Packaging

Packaging is wrappings, containers, or various protective elements, removable or permanent, with the primary purpose of enclosing, safeguarding, and prolonging the shelf life of products or simplifying their marketing. The realm of packaging constitutes a multifaceted technical and commercial framework, with the primary objective of safeguarding the enclosed content during its journey from production to consumption, while contributing to its recognition, promotion, and negotiation (Sastre et al., 2022).

In contemporary society, therefore, the packaging of goods plays a crucial role during their entire life cycle, from their creation and processing to their handling and eventual disposal (Ncube et al., 2021). In advanced economies, packaging accounts for about 2 percent of the gross national product, with a preponderance of packaging materials going mainly to the

food industry (Robertson, 2012). The packaging industry, however, expands to different application areas, from electronics to pharmaceuticals. Figure 1 provides a clear view of the sectors covered by this industry (WPO 2022).

The importance of it means that the packaging industry is constantly grappling with various challenges, such as the rise of e-commerce, the demand for more environmentally sustainable packaging solutions, and increasing regulatory requirements (WPO 2022).

Within this dynamic sector, the most relevant trends include the increase in the use of recycled and sustainable materials, spurred by a growing awareness of environmental issues. In addition, the proliferation of e-commerce platforms has generated greater demand for convenient and efficient packaging. The industry is embracing new technologies, including smart packaging and augmented reality packaging, to improve consumer engagement and experience. At the same time, stringent food safety and environmental conservation regulations are shaping the packaging landscape (WPO 2022).

Figure 1: The realm of the packaging industry

Source: Adapted from WPO (2022). *Packaging trends report worldstar award*.

While the primary focus of this thesis is centered on plastic packaging materials, it is pertinent to delineate the two principal forms that packaging may assume, namely, rigid and flexible packaging. Rigid packaging encompasses containers such as bottles, cans, boxes, and cartons, whereas flexible packaging comprises materials like plastic films, papers, foils, fabrics, and bags (Ncube et al., 2021).

Furthermore, it is important to introduce a nuanced classification pertaining to the three distinct categories of packaging, denoted as primary, secondary, and tertiary packaging. Primary packaging is primarily concerned with direct contact with products and serves the purpose of engaging with consumers directly. Secondary packaging is tasked with the consolidation of individual units (primary packages) for transportation and can be configured in a manner that makes them shelf-ready, thereby enabling the presentation of primary packages for promotional purposes within retail establishments. Tertiary packaging is designed to safeguard and streamline the handling of secondary packaged items (Ncube et al., 2021).

2.3 Plastic packaging

The packaging industry necessitates lightweight materials to minimize the quantity essential for product packaging, resulting in reduced transportation costs and decreased end-of-life packaging waste. Plastics have effectively fulfilled this role without encountering competition (Ncube et al., 2021). For instance, a study conducted by Marsh (2016), showed that the adoption of plastic bottles instead of glass bottles for beverage packaging in the airline sector led to savings exceeding USD 1 million in fuel expenditures, primarily due to the weight reduction.

The International Union of Pure and Applied Chemistry provides a definition for plastic as a “polymeric material that may contain other substances to improve performance and/or reduce costs” (Vert et al., 2012).

The primary source to produce plastics is fossil fuels, and a report from 2009 indicated that as much as 8% of the world's oil output was directed towards this purpose, with half of it serving as feedstock and the remaining 50% utilized as fuel during the conversion process (Al-Sale et al., 2009). A decade later, in 2019, the proportion of global oil production

dedicated to plastic manufacturing had increased to 10%, with 40% of this allocation specifically allocated to the production of single-use plastics (Jefferson, 2019).

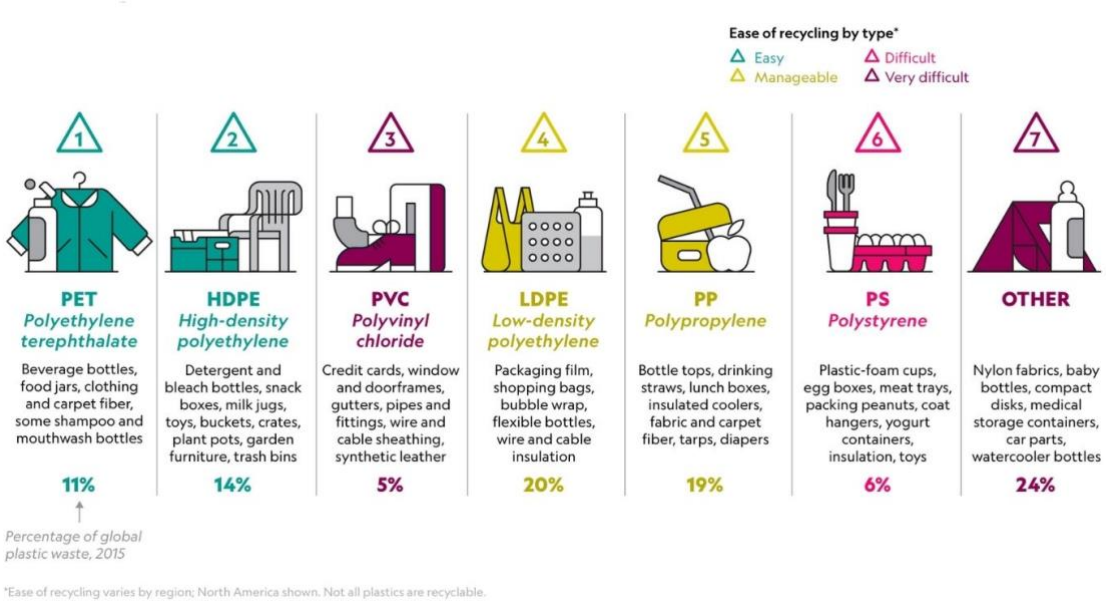
While it is not imperative to delve deeply into the chemical aspects of the plastic products under consideration for this thesis, it is still pertinent to establish a broader contextual framework to enhance comprehension.

Thermoplastics, constituting a significant 84 percent of the plastics market share, represent the primary category of polymers employed in packaging (Ncube et al., 2021). These thermoplastics belong to a polymer class that can undergo softening and liquefaction through the application of heat, facilitating various processing methods, such as thermoforming, extrusion, and injection molding (Mallick, 2010).

The production of thermoplastics involves the linking of minuscule molecules, known as monomers, through a process termed polymerization. A single polymer chain can comprise numerous monomers, and depending on the nature of these monomers, polymer chains may exhibit side branches. Polymer chains with few short side branches tend to form structured crystalline regions called spherulites, while those with abundant large side branches remain amorphous. Notable examples of amorphous polymers include polystyrene (PS) and polyvinyl chloride (PVC). Even in polymers with crystalline regions, there are typically some amorphous segments interspersed between the crystallites, classifying them as semi-crystalline. Common examples of semi-crystalline polymers encompass polyethylene (PE), polyamide (PA), and polypropylene (PP) (TWI, n.d.).

The subsequent figure 2 proposed by Parker, L. (2018) in his article "We Depend on Plastic. Now We're Drowning in It" is certainly helpful in illustrating the roles that these thermoplastics play within the plastic food packaging industry and offers a brief overview based on their recyclability characteristics.

Figure 2: Applications of thermoplastic



Source: Parker, L. (2018). *We Depend on Plastic. Now We're Drowning in It*

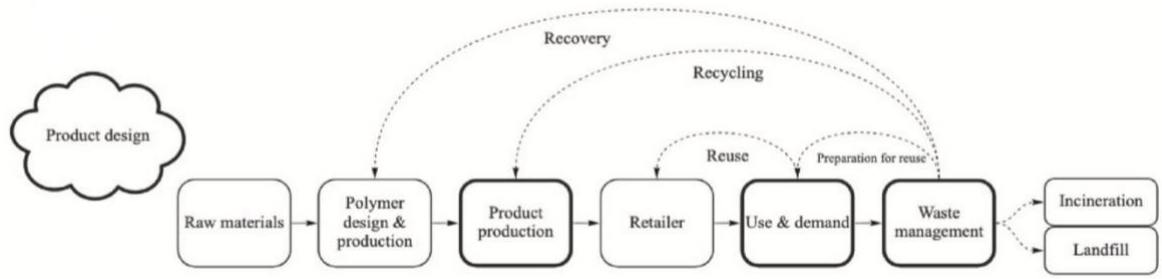
Petroleum-derived polymers, such as PP, PS, polyvinylchloride (PVC), PE, and polyethylene terephthalate (PET), have been extensively utilized for packaging due to their lightweight nature, favorable mechanical performance, effective barrier properties, and numerous other attributes. A significant proportion of these polymers eventually ends up in landfills, where their decomposition can take centuries to occur. Their non-biodegradable composition contributes significantly to environmental pollution (Ncube et al., 2021).

The packaging sector has initiated the incorporation of recyclable plastics in its designs as a strategy to curtail environmental waste. However, recyclers encounter challenges in maintaining contaminants at sufficiently low levels in the reprocessed plastic and meeting the criteria for the intended usage of the resultant packaging materials (Raheem, 2013). This undertaking has proven to be intricate, time-intensive, and resource-intensive due to the heterogeneous composition of collected plastic waste, necessitating sorting and segregation. Subsequently, the plastic waste might require thorough cleaning to eliminate residual contaminants from the products they once encased (Ragaert 2017). Furthermore, certain plastic additives, including well-known phthalates, exhibit durability within recycled plastic, giving rise to ongoing health concerns due to their low molecular weight, enabling facile migration from plastics into packaged food or water (Pivnenko et al., 2016).

2.4 Plastic value chain

This section will present an overview of the plastics VC with a perspective aimed at circularity. This representation is intended to show how achieving the CE requires more than just the use of particularly efficient recycling techniques, The progression towards a CE cannot be exclusively attained through alterations limited to the waste management system; instead, it necessitates integration with modifications occurring across various segments of the VC, encompassing design, production, and subsequent stages (Johansen et al., 2022). Figure 3 graphically presents the VC of plastics with a perspective of circularity. From the figure, it is possible to identify macro categories related to the design, production, use, and end-of-life phases.

Figure 3: Plastic value chain



Source: (Johansen et al., 2022).

2.4.1 Design

The design stage is the first part of the VC, where features and characteristics of the product are decided upon, including color, recyclability, and polymer composition (Iacovidou et al., 2019). This aspect emphasizes the reduction of plastic quantities, the creation of products using recycled plastic, or the development of products that are recyclable after their useful life. A prevalent theme in existing literature pertains to the challenge of designing packaging, particularly in the realm of food packaging, with reduced plastic usage or incorporation of recycled materials (Johansen et al., 2022). This challenge stems from the stringent quality requirements that food packaging must adhere to, encompassing low migration of harmful

substances, lightweight construction, and preservation of food freshness (Masmoudi et al., 2020).

Moreover, investigations within this domain establish that integrating recycled plastic into new products can prove intricate due to contamination stemming from varying polymer types, which can impact aspects like strength, toxicity, and weight (Johansen et al., 2022). The endeavor to integrate recycled plastic into novel products is met with two noteworthy challenges, as identified by Gall et al. (2020) and Iacovidou et al. (2019): contamination and mixing of polymers. Various guidelines for waste reduction and product recyclability assurance are highlighted in the literature. These guidelines include: 1) prolonging resource cycles by designing durable products and extending their lifespans; 2) recycling to close resource loops; 3) designing for sustainable sourcing; 4) optimizing resource utilization through design; 5) guaranteeing safe and ecologically sound product utilization; 6) preparing for extended product usage; and 7) creating designs that facilitate recycling (Johansen et al., 2022).

2.4.2 Production

The production stage entails a sequence of manufacturing procedures and usually involves the heating and molding of primary plastic, which is created by mixing crude oil at elevated temperatures to generate plastic polymers, into a variety of plastic products (Getor et al., 2020). Incorporating post-consumer recycled plastic into the plastic blend at this juncture carries several implications. Existing literature predominantly examines the effectiveness of blending recycled plastic with virgin plastic (Curtzwiler et al., 2019; Getor et al., 2020). These studies highlight several challenges associated with integrating recycled plastics into the manufacturing process.

A major obstacle is that recycled plastic often contains different types of polymers and is tainted with non-plastic substances such as additives. These elements can cause several issues, like the development of crystalline plastic clusters that are not evenly distributed, which lowers the value of the finished product (Getor et al., 2020). As indicated by Getor et al. (2020), one of the primary hurdles in utilizing recycled plastics lies in identifying the specific polymer type and identifying contaminants. This identification significantly impacts the feasibility of incorporating recycled plastic in the production process. In fact, the

qualities of recycled plastic degrade if mixed or contaminated polymers are used in the design of plastic items during garbage collection and sorting, hence tainting the waste stream (Getor et al., 2020).

2.4.3 Use

The third phase of the VC pertains to consumption, encompassing the aspects of plastic product demand, utilization, and disposal. Existing scholarly literature primarily directs its focus towards the procurement and demand stages, as well as the management of plastics in the post-consumer phase (Johansen et al., 2022). The divergence between the tangible environmental consequences and the perceptions held by consumers regarding such detrimental effects constitutes a principal impediment to achieving a circular economic model, as affirmed by the research of Boesen et al. (2019) and Núñez-Cacho et al. (2020). To surmount this challenge, it becomes imperative to enhance consumer awareness regarding the ecological footprint associated with their purchases. Nonetheless, the study by Núñez-Cacho et al. (2020) concluded that a substantial 69 percent of consumers do express concern regarding the ecological impact of plastics on the natural environment, indicating a general consciousness pertaining to plastic pollution.

During the process of product acquisition, consumer behavior is influenced by habitual practices, beliefs, knowledge, and prevailing social norms, thereby significantly influencing the demand for plastic products, as postulated by Núñez-Cacho et al. (2020). Adopting a more comprehensive standpoint concerning the usage phase of the VC, Clark et al. (2020) posit that the end-user assumes a pivotal role in the formulation of novel products and the augmentation of recycling rates. According to Clark et al., effecting a behavioral transition is of paramount importance for the successful implementation of a CE, given the influential role consumers play in shaping demand and the subsequent segregation of plastics after their utilization. Consequently, it becomes crucial to factor this facet into the conceptualization of remedies spanning the entire VC, although effecting alterations in consumer conduct may present notable challenges (Johansen et al., 2022).

2.4.4 End-of-Life

The ultimate phase, known as the end-of-life stage, encompasses the categorization and reprocessing of discarded plastic materials. An essential facet inherent within the CE framework is the assimilation of these waste components back into the manufacturing cycle to generate novel goods and services. Consequently, the end-of-life phase assumes a pivotal position within the CE paradigm, as emphasized by Bucknall (2020).

Collection and sorting: The main phase of waste management involves the processes of collection and categorization; current scientific work proposes several approaches for these tasks, including distinct separation methods such as the implementation of an "all-plastics bin" and tracer-guided sorting, systems these, designed to increase recycling rates of plastic waste (Johansen et al., 2022).

Recycling Technologies: analyzed in detail in section 2.8.

Within the domain of the plastic VC, scholarly discourse has attained greater maturity concerning subjects related to the termination phase of the plastic lifecycle. Nevertheless, it is worth highlighting that for the mitigation of plastic-associated waste and environmental contamination, it is imperative to engage in a comprehensive examination encompassing not solely the methodologies for plastic recycling, but also the establishment of a circular VC (Johansen et al., 2022). As posited by Bucknall (2020), the emphasis ought to be directed towards the formulation of a circular plastic economy as a proactive measure against plastic pollution. This necessitates a holistic approach encompassing not only recycling, but also factors such as design, utilization practices, and regulatory measures.

2.5 From the linear economy to the circular economy

For a long time, the linear economy has been the standard, yet it lacks the momentum needed to promote sustainable development. This method focuses mostly on obtaining raw materials, producing the product, finishing it, and finally disposing of it (Sharma et al., 2020).

One of the main causes of the current high levels of CO2 emissions and environmental damage is the unidirectional flow of plastics along the VC (Johansen et al., 2022).

A large amount of plastic is used only once in goods and packaging, and limited effort is made to recycle or reuse it (Dijkstra et al., 2020). As mentioned above, in Europe, approximately 23.4% of plastic waste was disposed of in landfills, 42.0% underwent incineration, and 34.6% was directed towards recycling (Plastics Europe, 2021). Despite a decreasing trend in landfilling, there is a concerning rise in incineration rates instead of transitioning towards recycling or reuse (European Commission, 2018).

In response to the prevailing "throw-away" culture and the deleterious consequences of the linear VC of plastics, which follows the "take, make, and dispose" model (Fig. 4) characterized by short periods of use and subsequent disposal, there has been a clear shift in perspective. This shift recognizes the finite nature of the Earth's resources used in the creation of these items, which are often only used for a limited period before being discarded (Ellen Macarthur Foundation, 2023) the CE therefore is gradually gaining traction.

Figure 4: Linear model “take, make, dispose”

Source: Adapted from “The LEAF Charity (2020). Trees and the Circular Economy”

A growing number of nations, corporations, and global organizations are developing plans to transition to a CE, which is defined by the three waste management choices of "Reduce, reuse, and recycle." The reuse concept deals with the continued use of items or components for their intended function, whereas the reduction principle seeks to decrease the usage of raw materials, energy input, and waste creation (Ghisellini et al., 2016). Recycling primarily serves to conserve energy, resources, and emissions, thereby reducing the environmental consequences associated with material usage. Although reduction and reuse are considered more environmentally friendly choices (Allwood, 2014), the utilization of recycled materials instead of virgin ones is generally perceived as a beneficial solution (Grosso et al., 2017). A focus is on enhancing the reuse and recycling of plastic (for example, initiatives by the Ellen MacArthur Foundation, 2020; European Commission, 2020).

A workable substitute for the existing linear system of plastics manufacturing, usage, and disposal is the circular plastics economy. Increasing the amount of plastic that is recycled or reused and reintegrated into the system is the main goal of the CE (Calleja, 2019; European Commission, 2018).

A circular plastic economy might result in a major decrease in the quantity of plastic that is disposed of in landfills, incinerators, and downcycling. Using a closed-loop production and consumption system, this method aims to turn plastic trash into a useful resource for the development of new goods (Johansen et al., 2022).

Even though the CE is becoming more and more popular, in Europe only 30% of plastic garbage is now collected for recycling, and a significant amount of that waste gets downcycled into materials that are less valuable than the original product (Calleja, 2019). The economy's primary causes of plastic downcycling include product designs that mix different types of polymers and contamination from organic and inorganic substances. These factors make it more difficult to create technically and financially viable channels for recycling plastic waste (M. T. Brouwer et al., 2018; Dahlbo et al., 2018). Managing PCW presents a distinct challenge, primarily due to its heterogeneous nature, which, as seen in this thesis, encompasses a diverse array of polymer types and additives. This waste stream often originates from products with short lifespans and single-use plastic packaging materials (Johansen et al., 2022).

2.6 Circular Economy: etymology and definitions

The introduction of the term CE has been attributed to Pearce and Turner (1990), as noted by several authors such as Andersen (2007), Su et al., (2013), and Ghisellini et al. (2016). In their seminal work, "Economics of Natural Resources and the Environment," Pearce and Turner examined the intricate relationship between the economy and the environment. In the context of the CE, they outlined the four economic functions of the environment (Andersen, 2007). The British environmental economists examined the features of the current linear economic system, which does not take waste management into account. Within this framework, natural resources are utilized as inputs to produce capital goods and commodities, with the goal of producing utility or well-being via consumption. This

paradigm views the environment as a trash container in addition to a source of resources for consumption and production.

In contrast, nature also produces waste, but unlike the economic system, it has inherent recycling mechanisms. Nature operates without landfills, as the waste of one species becomes nourishment for another. Powered by solar energy, the cycle of growth, death, return of nutrients to the soil, and subsequent restart perpetuates the sustainability of the natural system (Ellen Macarthur Foundation, 2023).

Considering garbage and its potential for recycling can help create a circular model where resources are collected, recovered, reused, upgraded, and repurposed (Pearce & Turner, 1989).

Even if the phrase "CE" was not used directly, the idea had already been presented by a number of writers. In his book "The Closing Circle," published in 1971, Commoner emphasized the imperative for the U.S. economy to align and conform to the immutable laws that govern nature, where waste does not really exist ("Everything has to go somewhere," the second law of ecology). Like the saying goes, "There's no such thing as a free lunch" (the fourth law), human well-being has historically frequently been pursued at the expense of Earth's natural resources, forcing an ultimate reckoning (Egan, 2007).

The European Commission commissioned Stahel and Reday-Mulvey to prepare a report titled "The Potential for Substituting Manpower for Energy," in which they introduced the idea of a ring economy. Under this system, waste production is reduced and products that have been utilized are converted into resources for others. The authors suggested a few strategies, such as technological updates, remanufacturing, rebuilding, repair, and repurposing, to increase the usable life of assets, components, and materials.

Stahel summarized the basic principle as "reuse what can be reused, recycle what cannot be reused, repair what is broken, and remanufacture what cannot be repaired" (Stahel, 2016).

2.6.1 Chosen definition

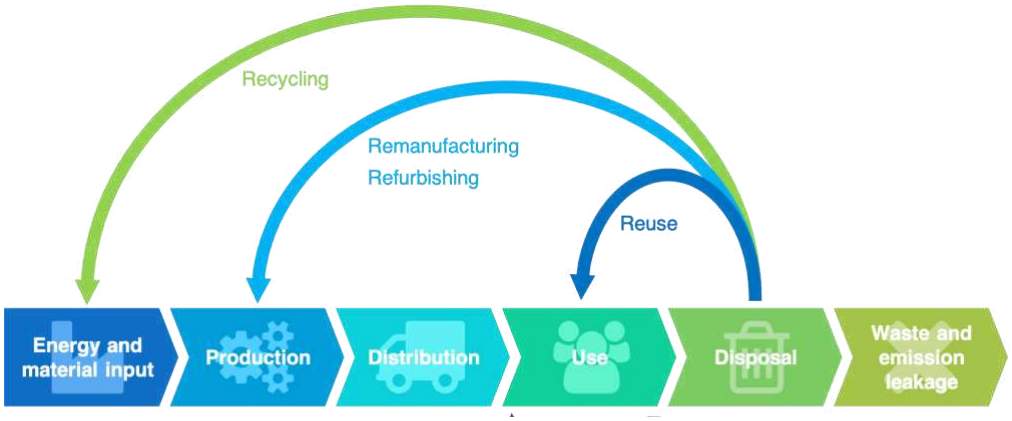
The concept of a CE remains a topic of considerable interest for both scholars and practitioners. A search conducted on Scopus in late 2021 yielded over 13,000 papers featuring the term "Circular Economy", with 7,800 (approximately 60 percent) published in

either 2020 or 2021. Geissdoerfer et al. (2017) conducted an analysis that demonstrated a noteworthy surge in publications on this subject, culminating in the emergence of 95 distinct definitions of CE (Kirchherr et al., 2023).

A number of these definitions have already been presented throughout this thesis, and as mentioned in chapter 1.1 *"Background of the study"*, the definition chosen is provided by the two authors Hahladakis & Iacovidou, 2019 who state that CE is "a system that has the capacity to restore, conserve and redistribute materials, components, and products (MCPs) in the best possible way and for as long as is environmentally, technically, socially and economically feasible". Figure 5 proposes a graphical representation of the concept just introduced where the curved arrows go to remember the typical concept of the CE considered the turning point to the more classical linear model.

This definition was chosen for its ability to provide a comprehensive perspective on the CE, encompassing various dimensions such as environmental, technical, social, and economic aspects. This holistic approach facilitates an in-depth exploration of the concept in the thesis. It is also characterized by its clarity and precision, which leaves no room for ambiguity as it explicitly outlines the essential attributes of a CE. Furthermore, by emphasizing that circular practices should be in line with environmental, technical, social, and economic feasibility, this definition recognizes and addresses the practical challenges and constraints often encountered in implementing CE principles.

Figure 5: CE from the point of view of the chosen definition



Source: Adapted from Geissdoerfer, M., Pieroni, M.P.P., Pigosso, D.C.A. and Soufani, K. (2020).

The definition offered by the two authors Hahladakis & Iacovidou, (2019) regarding a CE harmoniously aligns with the core principles of reuse, recycling, and reduction (Ghisellini et al., 2016).

The principle of reuse finds strong support in this definition through its emphasis on the capacity to restore and conserve Materials, Components, and Products (MCPs) for extended periods. Rather than discarding these items after their initial use, the definition advocates for their maintenance and refurbishment, thus promoting the ethos of reuse.

Additionally, the concept of recycling is endorsed by highlighting the capability to efficiently redistribute MCPs. As materials and products reach the end of their functional lifespan, the CE's approach encourages their transformation into new materials or products. This practice significantly reduces the necessity for virgin resources and minimizes the generation of waste.

Finally, while not explicitly stated, the principle of reduction is indirectly addressed within the definition. This is achieved by underscoring the importance of managing MCPs optimally, in a manner that aligns with environmental, technical, social, and economic considerations. By optimizing both the usage and longevity of materials and products, the CE strives to curtail the overall demand for new resources while simultaneously reducing waste generation.

2.7 European regulatory framework on the circular economy

Over the past decade, the concept of the CE has emerged as a focal point in EU policies. This new paradigm aims to reduce the extraction of natural resources by exploiting their profitable reuse (Zarbà et al., 2021). For this purpose, it is useful to analyze the European regulatory landscape in this field in order to have a general overview of the measures adopted to date.

Europe has undoubtedly emerged as a global vanguard in the continuous search for a CE, as exemplified by the European Green Deal and the many directives articulated by the European Union over the years.

As part of this research, the examination is specifically directed at the intricate web of regulations, policy directives, and instruments meticulously formulated and implemented to promote the principles of circularity, particularly within plastics, throughout the European

region. This academic effort aims to clarify the central and predominant role played by the European regulatory framework, not only in guiding the trajectory towards a more sustainable and regenerative future, but also in its ability to be a pre-eminent model that guides the efforts of supporters of the CE on a global scale.

Table 1, European Regulatory framework, shows some of the most important measures adopted so far with a specific focus on the main objective that they aim to achieve and, above all, on the measures that have as their main theme that of plastic.

Table 1: European regulatory framework

Directive	Name	Objective	Measures
EU directive 2019/904	*reducing the environmental impact of certain plastic products*	Reduce waste generation and promote sustainable production and consumption practices, in line with the UN's 2030 Agenda for Sustainable Development adopted on September 25, 2015.	a. Banning certain single-use plastic products like straws, plates, and cutlery from being sold. b. Requiring the availability of reusable or compostable alternatives for these products. c. Introducing a tax on single-use plastic items. d. Running awareness campaigns to cut down on the use of such products.
Directive 94/62/EC	*packaging and packaging waste*	Promote uniform packaging and packaging waste management measures across EU countries and foster positive environmental impact by preventing and reducing the effects of packaging and packaging waste.	a. Promoting national programs and extended producer responsibility (EPR) schemes. b. Use economic instruments to reduce packaging waste, including deposit return systems. c. Establish recycling targets for plastic packaging (50% by 2025, 55% by 2030). d. Requirements: Limit the weight and volume of packaging, ensure product safety and hygiene, reduce hazardous substances, and design reusable or recoverable packaging.
Commission Regulation (EU) 2022/1616	*Recycled plastic materials and articles intended to come into contact with food*	Ensure the safety of human health and the environment when employing recycled plastics in products intended for food contact, while also	a. New requirements for the use of recycled plastics in food contact materials. b. Tracking and labeling system for items made from recycled plastics to monitor and ensure safe and sustainable use.

		promoting their sustainable use.	c. Specification of two valid recycling processes: - Mechanical recycling of post-consumer PET with strict conditions. - Recycling within closed, controlled chains for plastics explicitly intended for food contact, with requirements such as high-temperature microbiological decontamination and surface cleaning.
Commission Communication 2019/640	*The European Green Deal*	Achieve climate neutrality in Europe by 2050. It aims to reduce GHG, promote renewable energy sources, enhance energy efficiency, and protect the environment.	The EU focuses on transitioning to a CE, which includes minimizing waste, encouraging reuse, and promoting recycling of materials, including plastics, wherever feasible.
Commission Communication 2020/98	*A New Circular Economy Action Plan for a Cleaner and More Competitive Europe*	The main objective is to establish a CE in Europe by enhancing product sustainability, improving waste management, and promoting the use of secondary materials in products, ultimately reducing waste and benefiting the environment and economy.	a. Measures to improve the durability, reparability, and recyclability of products, including consumer goods, including plastic products. b. Ambitious recycling targets, and measures to facilitate the reusability of products. c. Establish a legal framework for the use of secondary materials in construction projects.

Source: personal production based on data collected by the above-mentioned laws

Europe is committed to addressing the urgent problems caused by environmental concerns and climate change. The ambitious European Green Deal program, which aims to transform the EU into a contemporary, resource-efficient, and internationally competitive economy, is one example. It aims to achieve two main goals: zero GHG by 2050 and promote resource-independent economic growth while ensuring equitable prosperity for all people and areas. The plastics industry is one of the key sectors affected by this transformation framework (EC/2019/640).

In 2020, the Commission introduced a new CE Action Plan as the cornerstone of the European Green Deal global initiative. With a focus on resource-intensive sectors, the Action Plan, which includes plastics, aims to promote sustainable product design, empower

consumers and public purchasers, and promote circularity within production processes (EC/2020/98).

Within the framework of the abovementioned action plan, a proposal was submitted to establish mandatory standards concerning the incorporation of recycled plastic content into key product categories, including packaging, construction materials, and vehicles, with the ultimate goal of stimulating wider adoption of recycled plastics (EC/2020/98). Previous measures have already been taken under the single-use plastic directive, which outlined specific requirements for beverage bottles. For example, by 2025 PET bottles must contain at least 25% recycled plastic and by 2030 this content must increase to 30% for all bottles (EU/2019/904).

In addition, the European Green Deal foresees a significant role for packaging. By 2030, the plan aims to ensure that all packaging can be effectively reused or recycled in a cost-effective manner (EC/2019/640). The Packaging and Packaging Waste Directive also set ambitious targets, with the target of recycling 50% of plastic packaging material by 2025 and raising the bar to 55% by 2030 (EU/2018/852).

2.8 Plastic recycling

According to Dijkema et al. (2000), “waste is only a temporary attribute of a resource”. Every material is a component in at least one material cycle, which also involves waste treatment and the usage stage.

Plastic waste is acknowledged to possess the capacity for transformation into a reusable resource through a series of appropriate procedures. The overall count of feasible material circuits is contingent upon the material's deterioration across each phase of its lifecycle (Horodytska et al., 2018). The following sections briefly present how plastics are recycled, at the end of which Table 2 will present the main criticisms of the various recycling techniques illustrated.

2.8.1 Mechanical recycling

Mechanical recycling uses a variety of mechanical techniques while preserving the product's polymer composition. Because of this method's economic and technological feasibility, it is extensively used. The ultimate use of the recycled product distinguishes between two possible configurations: closed-loop and open-loop (Horodytska et al., 2018).

The recycled material in the closed-loop process has characteristics and attributes that are similar to the original, which makes it appropriate for producing high added-value products. Usually, there is just one kind of plastic in the input garbage, and it is not very contaminated. By melting and re-granulating the plastic during the extrusion process, the waste is transformed. This process of recycling is also known as re-extrusion. Periodically, procedures for decontamination might be used before re-granulation (Horodytska et al., 2018).

On the other hand, open-loop mechanical recycling entails a sequence of mechanical procedures such as re-granulation, washing, drying, and shredding. The input waste consists of one polymer substance or a blend of plastics that work well together. Plastic additives, inks, and incompatible polymer residues are examples of impurities found in the waste stream that might affect the qualities of recycled plastic during reprocessing and limit its acceptability for less demanding applications including trash bags, pipes, and agricultural items (Horodytska et al., 2018).

2.8.2 Chemical recycling

Chemical recycling is centered on the disintegration processes of the polymer structure with the aim of acquiring the original monomers or valuable alternative chemicals. The resulting recycled goods can be employed as raw materials for the production of fresh polymers. The principal methods of chemical recycling encompass depolymerization (methanolysis, glycolysis, and hydrolysis), partial oxidation (gasification), and cracking (pyrolysis). Pyrolysis, which includes both thermal and catalytic variations, is extensively utilized for recycling polyolefins and other additive-based polymers. The products yielded from pyrolysis consist of liquids and gases that encapsulate the desired components. Frequently,

the costs associated with separation procedures are deemed excessive, resulting in the repurposing of recycled products as fuel sources (Horodytska et al., 2018).

2.8.3 Incineration

The extraction of energy from plastic waste through incineration (combustion) is pursued as a waste management strategy. Incineration of waste materials is employed for the generation of electricity and district heating, achieving efficiencies surpassing 90%. Due to their elevated calorific value, plastic products serve as a notably abundant source of energy materials. Following the incineration process, waste volume reduction reaches levels of 90–99%, thereby presenting a substantial advantage in scenarios characterized by spatial limitations and restricted landfill capacities. Additionally, the incineration process serves to eliminate chlorofluorocarbons (CFCs) and other hazardous compounds (Horodytska et al., 2018).

Plastic garbage is incinerated using a variety of ways. Co-incineration is the process of burning municipal solid trash and a significant amount of plastic garbage at the same time. It is carried out using fluidized bed combustion, one-stage, and two-stage methods. When it comes to cement production, waste plastic solids are often used as fuel in cement kilns, which helps to reduce energy costs. In a similar vein, blast furnaces offer a widely used method of getting rid of plastic trash (Horodytska et al., 2018).

Despite the economic and certain environmental advantages, energy recovery approaches deviate from the principles of the CE, which advocate for the management of plastic products within closed-loop systems. Consequently, priority is accorded to reuse and recycling methods in waste management, with energy recovery being applied to non-recyclable fractions (Horodytska et al., 2018).

Table 2: Plastic recycling process: Criticisms

Plastic recycling process	***Criticisms***
MECHANICAL RECYCLING	Loss of qualities. Use of energy and resources. The presence of additives or mixed materials can jeopardize the recycling.
CHEMICAL RECYCLING	Difficult for some plastics to recover *selectively* the starting materials. Use of energy and resources. The presence of additives or mixed materials can jeopardize the recycling.
INCINERATION	The material cannot be re-used in the production cycle but energy is recovered. Life Cycle Assessments are necessary to evaluate which way is the most sustainable.

Source: (Mariotti et al., 2019)

3 Industry 4.0 and Circular Economy

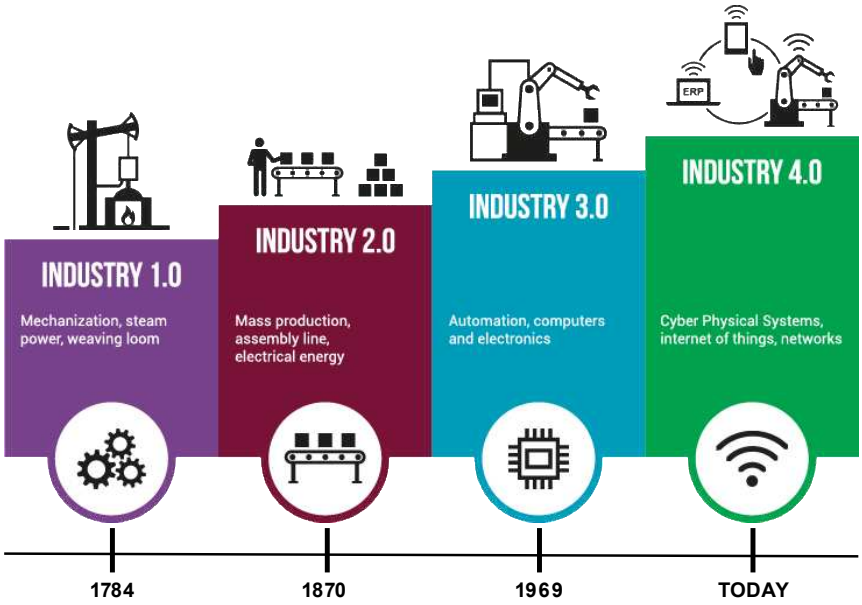
3.1 From industry 1.0 to industry 4.0

In earlier centuries, various items such as food, clothing, housing, and weapons were made through manual labor or with the help of domesticated animals. The manufacturing landscape underwent significant transformations with the advent of the first industrial revolution in the early 19th century, initiating a rapid progression of industrial processes. At the heart of industrial automation is the critical issue of creating reliable information exchange. A constant information flow between sensors, controllers, and actuators is necessary for any attempt to mechanize processes in order to minimize or eliminate human involvement. To support this evolution, numerous industrial communication networks have grown over time (Rao and Prasad, 2018).

CPS serve as the foundation for Industry 4.0 today. Industry 4.0, which combines the Internet of Things (IoT) with manufacturing techniques, makes it easier to exchange, analyze, and use data for wise and well-informed decision-making. Additionally, it embraces cutting-edge technology including improved materials, augmented reality, robots, AI, and other cognitive technologies, as well as additive manufacturing (Rao and Prasad, 2018).

Figure 6 "The Four Industrial Revolutions" depicting the stages of industry, from 1.0 to 4.0, is intended to help the reader for a better understanding of the concepts presented.

Figure 6: The four industrial revolutions



Source: adapted from (Hare, 2018)

3.2 Industry 4.0 definitions and enabling technologies

The term "Industry 4.0" was first used in 2011 as a part of a collaborative project between the German federal government, academic institutions, and private businesses. This program was closely linked to a strategic initiative that was intended to support the creation of highly sophisticated production systems with the ultimate goal of increasing the productivity and efficiency of domestic industry in Germany (Cannavacciuolo et al., 2023).

The World Economic Forum's founder and executive chairman, Klaus Schwab, stated in a 2016 article that the Fourth Industrial Revolution is building on the Third, or the digital revolution that has been going on since the middle of the 20th century. It is typified by a merging of technologies, making it more difficult to distinguish between the digital, biological, and physical domains. Three factors—velocity, scope, and systems impact—indicate that the current changes herald the entrance of a Fourth and distinct Industry 3.0, rather than just its extension.

Industry 4.0 is characterized by "short production runs of mass-customized goods, the global fragmentation of VCs, the networking of productive capacities and blurring of boundaries

between industry and the services sector on the one hand and producers, sellers, and consumers on the other" (Caruso, 2017).
The scientific community and practitioners have been paying more and more attention to Industry 4.0, which is regarded as a highly relevant study issue (Cannavacciuolo et al., 2023).

In this specific segment of the thesis, denoted by Table 3, an exposition of the diverse technologies constituting the current industrial revolution will be provided, accompanied by concise descriptions. In a subsequent section, denoted as paragraph "*3.4.4 Enabling technologies*", a comprehensive analysis will be conducted specifically focusing on those technologies which, in accordance with existing literature, align most closely with the principles of the CE for plastics, thereby becoming the central focus of this thesis.

Table 3: Industry 4.0 technologies

Technologies	**Description**
Additive manufacturing (3D printing)	employs a number of additive or layered development frameworks to produce three-dimensional (3D) solid items in manufacturing.
AI	is a branch of computer science that focuses on building intelligent machines that behave and think like people.
Augmented reality	is a kind of interactive, reality-based display environment that enhances the real-world experience by utilizing computer-generated sound, graphics, and other effects.
Autonomous robots (Robotics)	are employed in production to mimic human behavior.
Big data and analytics	Analysis of large volumes of data that are used with the purpose of discovering the insights and meaning of the underlying data.
Blockchain	is a distributed database that uses modern encryption and authentication technologies along with a network-wide consensus process to maintain an entirely distributed, non-tampering, continually increasing list of records.
Cloud	refers to any cloud computing provider-provisioned and accessible IT services.
Robotic systems	is a robot designed to engage in hands-on interaction with people in a shared workspace.
Cybersecurity	refers to proactive measures taken to guard against data theft, breach, and attack.
Unmanned aerial vehicles (Drones)	is a term used for an aircraft that does not have a human pilot on board, also known as a drone.
Global Positioning System (GPS)	is a technological marvel that is made feasible by a constellation of satellites in Earth's orbit that send precise signals, enabling GPS

	receivers to compute and present to users accurate location, speed, and time data.
Industrial IoT	is the collection of different hardware components that interact with one another via IoT connectivity to improve industrial and manufacturing operations.
Mobile Technology	is the wireless communication technology integration based on the wireless devices.
Nanotechnology	technology of manipulating individual atoms and molecules to fabricate large-scale things, also known as molecular nanotechnology.
RFID	Communication between an object (or tag) and an interrogating device (or reader) to automatically track and identify such objects.
Sensors and actuators	is a device that transmits an impulse in response to a physical stimulus (heat, light, sound, pressure, magnetism, or a specific motion) (as for measurement or controlling a control).
Simulation	Refers to technologies that use the computer for the imitation of a real-world process or system.

Source: Adapted from (Bai et al., 2020)

3.3 Industry 4.0 and circular economy

Industry 4.0 and CE have unquestionably emerged as two of the most extensively discussed subjects in recent decades. Over time, they have garnered the attention of policymakers, professionals, and academics worldwide (Rosa et al., 2019).

When conducting independent searches on Web of Science using "Industry 4.0" and "Circular Economy" as keywords, it retrieved 39,000 and 25,777 documents, respectively, as of October 2023. However, there has been relatively limited exploration into the intersection of these two themes. When employing both "Industry 4.0" and "Circular Economy" as search terms, only 761 papers were found, with 390 of them being published between 2022 and 2023.

The CE and Industry 4.0 are examples of new organizational and technological innovations that can improve a business's capacity for long-term production. The importance of adopting Industry 4.0 technologies has increased dramatically as a result of the constant demand for domestic and foreign enterprises to meet sustainability targets. An organization's operational, environmental, economic, and manufacturing performance can all be improved by integrating Industry 4.0 technologies, which encourage greater transparency and efficiency throughout the SC (Tang et al., 2022). Singh et al. (2021) have found a strong

correlation between Industry 4.0 and the CE. The impact of Industry 4.0 on operational, environmental, economic, and SC performance makes it possible to leverage and improve SC performance through the adoption of inter-organizational systems (Singh et al., 2021). Consequently, the incorporation of Industry 4.0 technologies can facilitate the digitization of the SC, providing timely operational and strategic information that enhances SC capability and contributes to the improvement of the CE. Advanced technologies, as suggested by Latan et al. (2018), offer cost-saving opportunities and long-term revenue benefits for companies. The adoption of Industry 4.0 technologies in conjunction with CE principles, coupled with an effective "information sharing strategy," can significantly enhance SC operations, enabling them to achieve operational excellence, as demonstrated by Alkhuzaim et al. (2021). Upon a preliminary review of the literature, it is apparent that experts commonly agree that Industry 4.0 can act as a catalyst for the CE. Any company aspiring to adopt circular practices must inevitably consider the integration of Industry 4.0 technologies within its VC (Rosa et al., 2019).

Table 4 illustrates the outcomes of a study conducted by Capetillo et al. (2022), showcasing 15 Industry 4.0 technologies that are pertinent to the shift toward circularity within the plastics VC. This study accentuates the central role of IoT, AI, and Blockchain technology in the discourse concerning the transition to a CE (Capetillo et al., 2022).

Table 4: Emerging technologies by number of mentions

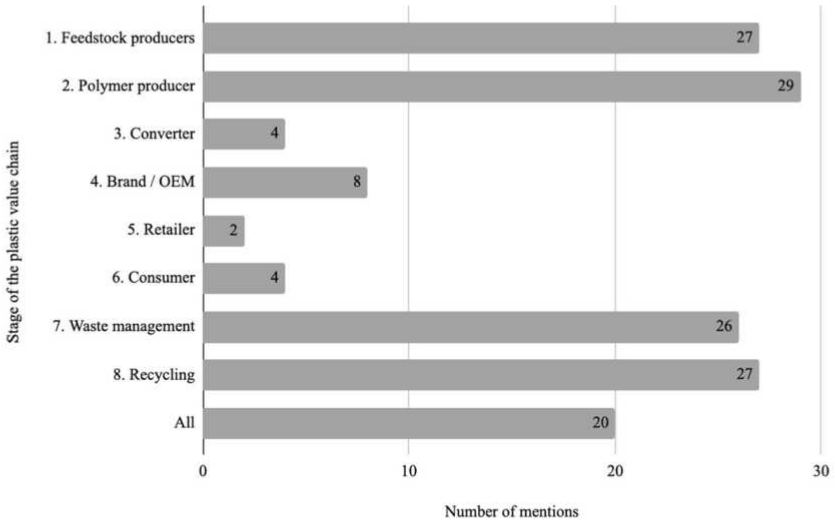
Technologies	Number of mentions in the literature	Technology set *I4.0*
Biopolymers	24	
Biorefineries	23	
Internet of Things (IoT)	16	X
Artificial Intelligence (AI)	14	X
Blockchain	14	X
Synthetic Biology	12	
Nanotechnologies	11	X
3D Printing	10	X
Robotics	10	X
Chemical Recycling	10	
Big Data	9	X
Cloud Computing	7	X
Augmented and Virtual Reality	5	X
Process Intensification	4	X
Microrecycling	3	

Source: Own adaptation from Capetillo et al., 2022 (based on 55 articles)

When we delve into the specific technologies examined, a noteworthy revelation pertains to the VC stages to which these emerging technologies are applicable. As is evident in Figure

7 the majority primarily pertain to the initial phases of the VC, which encompass the production of raw materials and polymers. Conversely, the second largest cluster is associated with the concluding phases related to waste management and recycling. The intermediate stages of the plastics VC receive relatively limited attention. Significantly, an additional set of 20 articles presents technologies that exert an influence across all phases of the VC, suggesting their potential to instigate systemic-level transformation (Capetillo et al., 2022).

Figure 7. Impact of industry 4.0 on the plastic value chain stages by number of mentions



Source: Capetillo et al., 2022 (based on 55 articles)

The literature emphasizes the technologies' potential for synergy, going beyond their respective applications. We can distinguish four different groups of new technologies that have the potential to upend the current plastics materials regime in four different ways: First, through increasing productivity and automation (which is related to Industry 4.0); Second, through enabling a change in the production-consumption system (which is related to distributed economies); Third, through encouraging the creation of high-value products made from biological materials (which is related to biobased systems); and Fourth, by reducing the amount of raw materials needed to make high-quality recycled plastics (which is related to chemical recycling) (Capetillo et al., 2022).

Focusing on the first aspect, research indicates that Industry 4.0 technologies, through data interchange and automation capabilities, hold significant promise for promoting circularity

in the production stages of the plastics VC. Positive incentives in this category of technologies include the potential for increased production and efficiency, the development of consumer-focused marketing messages, the potential integration of various waste sources, the possibility of increased material reusability, chances for stakeholder collaboration and transparency, and a sizable societal impact that is consistent with current policy discussions (Capetillo et al., 2022).

What has just been stated is a focal point of this thesis. In the following sections, a more specific definition of traceability will be explored and its successful implementation in some projects within the agribusiness sector will be explored.

In addition, the technologies that, according to currently available literature, are best suited for this type of practice will be reviewed, studying their basic architecture and applications in the context of sustainable SC.

3.4 Definition of traceability

Numerous interpretations pertaining to traceability are available, with a significant portion of them being present within the standards and regulations of the food industry (Schuitemaker and Xu, 2020).

The primary widely recognized definitions of traceability, both in the broader context and specifically related to SC matters, can be traced back to the ISO9000:2015 and its preceding iterations, the Global Standards One (GS1) Traceability standard as discussed by Garcia-Torres et al. (2019) and in the works of Schuitemaker and Xu (2020).

ISO9000:2015 defines traceability as the “ability to trace the history, application or location of an object by means of recorded identifications, where “object” includes tangible and intangible entities” (ISO 9000: 2015).

GS1 (2012), refers to traceability as "the ability to track forward the movement through specified stage(s) of the extended SC and trace backward the history, application or location of that which is under consideration (GS1, 2012).

In addition to this, various definitions arise contingent upon the context of reference, and numerous scholars have undertaken the task of formulating a comprehensive, universally applicable definition. Of particular significance, Oslan and Borit have presented a contemporary definition of traceability as "the ability to access any or all information relating to that which is under consideration, throughout its entire life cycle, by means of recorded identifications" (Olsen and Borit, 2013).

In the past, investigations into traceability primarily focused on quality and safety considerations, with limited attention paid to sustainability, as noted by Katenbayeva et al. (2016). Presently, the traceability of products and processes has gained prominence as crucial information in facilitating the transition towards a CE. This transition aligns with the objective of attaining “Sustainable Consumption and Production” as articulated in SDG12 by optimizing resource utilization and minimizing waste generation (Giovanardi et al., 2022).

Ensuring traceability throughout the entire VC holds significant potential for attaining success in the pursuit of these objectives. Traceability technologies offer a valuable repository of digital data pertaining to suppliers upstream, who furnish raw materials, partners downstream, who enhance the product, customers making purchases, and all associated processes throughout the chain. Enhanced transparency into both inputs and procedures furnishes the capabilities required to realize sustainability goals (Betti, Hinkel, and Saenz, 2021).

3.4.1 Traceability in supply chain

SCs have been used by global manufacturing networks as a common organizational structure. One of the most important inter-organizational mechanisms for creating a competitive advantage is the management of SCs, particularly in the context of networks and alliances between suppliers and customers. The burgeoning pace of technological advancements, the widening scope of globalization in trade, and the growing emphasis on environmental accountability have engendered a heightened customer demand for enhanced adaptability, velocity, information accessibility, and product tractability. These factors have collectively driven the recent expansion of SCs (Dasaklis et al., 2022).

In light of globalization, the unpredictability of customer expectations, the proliferation of product varieties, uncertainties surrounding supplier performance, and a plethora of other factors, SC networks have become increasingly intricate. This complexity has resulted in the escalated production and movement of goods and commodities to geographically distant locations (Ateş et al., 2021). Present-day SCs exhibit considerable diversity, featuring a multitude of hierarchical levels and geographically dispersed businesses struggling to cater to the needs of their customers (Dasaklis et al., 2022).

Consequently, it is progressively challenging to retrace each stage of a product's journey back to its point of origin. Certain aspects of SCs can be particularly enigmatic, owing to the involvement of numerous stakeholders and multi-layered structures, each with distinct systems and requisites (Dasaklis et al., 2022).

In recent years, traceability systems have emerged as powerful instruments to improve the transparency of SCs, particularly within the framework of multinational SCs. Consumers, business executives, legislators, and interest groups have all come to accept these systems as essential tools for ensuring the quality and safety of goods, especially in industries where health and safety are important concerns, like the food and pharmaceutical sectors (Dasaklis et al., 2019). These traceability systems furnish SC networks with the means to meet regulatory obligations, establish connections, and comprehend the various upstream participants in the SC, inform consumers about the origins and provenance of products, boost consumer confidence, and cater to customer demands (Dasaklis et al., 2022).

Businesses can discern opportunities for enhancing the entire SC, identifying and eliminating superfluous intermediaries, and crafting more effective long-term plans by accumulating and scrutinizing comprehensive data on SC performance metrics (Dasaklis, Casino, and Patsakis, 2019)

Effective inter-organizational communication is crucial in today's integrated global economy (Arora et al., 2021). Partners within SCs must clearly identify their objectives, incorporate proper data collecting and validation techniques into their strategy, and choose the right technology to meet their needs in order to achieve their sustainability goals. Additionally, transparency in an SC reduces dangers to one's reputation and improves the dependability of corporate operations (Dasaklis et al., 2022).

3.4.2 Industry 4.0 tracking systems in the agri-food sector

During the comprehensive examination of the relevant literature within the context of this thesis, numerous scholarly works have been identified that pertain to the monitoring and traceability services within the Agri-food SC.

Agri-food sector

When it comes to the food industry, the principal rationale behind the adoption of food traceability services resides in the capacity of these systems to facilitate a comprehensive understanding of the safety and origin of perishable food items. This is achieved through the meticulous tracking of their production, handling, storage, and the conditions under which they are transported or processed. Consequently, this careful monitoring results in the production of an open and genuine record of the food ecosystem (Godsiff, 2016). Within the realm of the food industry, the acquisition of provenance and traceability information plays a pivotal role in the enhancement of food quality and safety. Moreover, the advent of emerging technologies, particularly in the era of Industry 4.0, holds significant promise in mitigating unwarranted wastage and diminishing the ecological impact associated with issues such as product recalls, disease outbreaks, cross-contamination, and related concerns. In this regard, a number of sectors are seriously considering the use of cutting-edge technologies like blockchain and the IoT to improve traceability procedures (Kayikci et al., 2020).

There are not many blockchain technology-based prototype applications in the food business right now. A business called Provenance developed the first experimental program for tracking food using blockchain technology. From fishermen to distributors and merchants, and from the shore to the plate of the consumer, every step of the SC for yellowfin and skipjack tuna was meticulously monitored. Anybody with a Radio-Frequency Identification (RFID) tag, QR code, or other unique identifier associated with the item—or with any other hardware technology—could access the digital record, which was safely kept on the blockchain. This made it possible for customers to follow the path of their tuna sandwiches from start to finish using a smartphone and to learn about the suppliers, manufacturers, and all pertinent procedures (Kayikci et al., 2020).

In 2017, Deloitte created a second “food chain” prototype that can track every ingredient in a specific product all the way through the SC. With the use of a smartphone app using this technology, a Chinese consumer may be able to choose a product, scan the RFID label, and learn more about the product’s ingredients’ origins (Deloitte, 2017).

Moreover, Carrefour unveiled a blockchain-based product monitoring system for their quality line at the beginning of 2018. A network of chicken producers participated in the original study, which included every stage of the process from hatching to farming, slaughter, processing, and distribution. The package for the chicken used a straightforward QR code. Subsequently, the solution was expanded to cover four other products: tomatoes, eggs, milk, and Rocamadour cheese (Carrefour 2018).

3.4.3 Enabling technologies

Based on the illustrations provided in the preceding section, it becomes evident that the novel technologies of Industry 4.0 play a pivotal role in ensuring the effective monitoring of the entire SC.

These cutting-edge technologies are actively contributing to the metamorphosis of traditional SC networks into advanced digital systems that enable heightened visibility, enhanced collaborative capabilities, and improved operational efficiency (Khan et al., 2022). Technologies aimed at facilitating traceability and transparency have, as a result, become indispensable instruments for coordinating and disseminating information among stakeholders across the entire SC (Khan et al., 2022).

The research carried out for this thesis showed that the most suitable Industry 4.0 technologies for traceability are blockchain technology, IoT, and AI.

3.4.3.1 Blockchain technology

Introduction

Since its inception in 2008 through the introduction of Bitcoin cryptocurrency by Nakamoto, blockchain technology has gained prominence as a secure and decentralized system for managing transactions and data. It has found widespread application in various commercial sectors, including value-chain and SC management, in addition to its utilization in the realm of cryptocurrencies (Narayan and Tidström, 2020).

Blockchain technology is centered on its technical features, which facilitate the creation of distributed digital ledgers that can self-authenticate through predefined consensus mechanisms involving multiple participating entities (Nandi et al., 2021). While there are various definitions of blockchain technology, it can generally be characterized by four fundamental attributes: decentralized consensus, information-sharing, incentivization, and negotiation mechanisms, (Saberi et al., 2019).

Blockchain serves as a versatile platform that accommodates a range of other technologies, such as big data, IoT, and AI. Despite encountering certain technological challenges, blockchain systems offer unique capabilities that are unmatched by other systems, including transparency, traceability, security, real-time data access, and the implementation of smart contracts (Nandi et al., 2021).

Moreover, it is possible to integrate blockchain technology with other technologies like the physical internet, RFID, cloud computing, sensors, and more, as highlighted by Treiblmaier (2019).

Blockchain Architecture

The blockchain operates through a set of key components (Puthal et al., 2018).

- Transaction: This serves as the logical processing unit, encompassing a sequence of elementary transactions that require verification, approval, and subsequent storage.
- Node: Representing an individual actor within the blockchain, a node is physically manifested as a server.
- Block: A collection of related transactions consolidated for the purposes of approval, storage, and verification.

- Ledger: The ledger where every transaction is sequentially arranged and immutably recorded.
- Hash: An irreversible computational function that creates a unique string of a predetermined length out of a variable-length text or numeric string.

Blockchain technology makes it easier for people to store and share data in an open virtual environment. Users can access all transactions simultaneously and in real-time thanks to it (Wang, Han, and Beynon-Davies, 2019).

Every block creates a digital fingerprint by combining information from all system transactions that took place during a given period. This fingerprint establishes a link to the following block and confirms the accuracy of the data (Beck et al., 2016). The blockchain can support several of these blocks, connected in a chronological and linear fashion, where each block contains a hash of the one before it. Any alterations to the ledger's stored information necessitate consensus approval from every node in the network. This capability arises from the transparency of the data infrastructure within a blockchain, where no single entity exercises control over the data (Kayikci et al., 2020).

Blockchain and sustainable supply chain

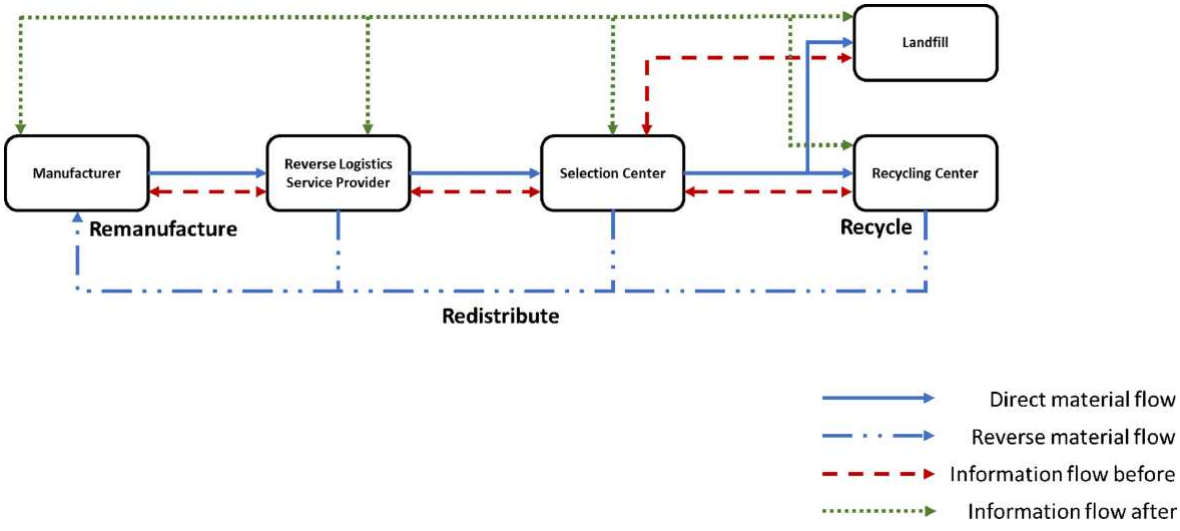
Within the context of SC management, Blockchain Technology operates as a decentralized transaction ecosystem where participating members collaboratively agree to share data while concurrently verifying the accuracy of the shared information. This data encompasses a wide array of elements, including inventory data, digital assets, machinery operational status, payments, logistics and shipping statuses, business process records, and any other relevant information (Nandi et al., 2021).

In a blockchain environment, data is organized into blocks, which are continually appended to an immutable ledger that is accessible to all SC participants. This transparent sharing of information enhances traceability on both global and local scales within SC scenarios. Blockchain's decentralized consensus and information-sharing features significantly enhance visibility and transaction efficiency in the SC, crucial aspects for preemptive actions or responses in the event of disruptions (Nandi et al., 2021).

Blockchain technology furnishes stakeholders with dependable, secure, and transparent data, along with additional features that augment the value of SC operations, resources, materials, products, and processes (Narayan and Tidstrom, 2020).

Four key players play crucial roles in a blockchain-based SC: certification authorities, which grant participants unique identities; network administrators, who establish standardized schemes such as blockchain policies and technology requirements for the network; membership service providers, which issue certificates to participants in order to engage with the network; and other actors, which include manufacturers and reverse logistics service providers. When a new actor joins the network, the certifying body first evaluates if the new user is qualified to perform the assigned responsibilities before establishing a temporary account with restricted features (Centobelli et al., 2021). Information about the product is gathered at every stage. A sample circular SC operation is shown in Figure 8, which shows the movement of information and items both before and after blockchain technology was implemented (Centobelli et al., 2021). There are two distinct material flows in the circular VC: a closed loop and a linear loop. Whereas the latter relates to material recycling, the former depicts a direct material flow cycle (Centobelli et al., 2021). Depending on how widely blockchain technology is used, information flows in different directions. Every participant will be able to freely share information with all SC partners after blockchain adoption. All transactions are handled by smart contracts, which are used to speed up and improve transactions between various users. Smart contracts run automatically and without intervention on all network nodes, according to the data contained in the transaction. The blockchain records all of the transactions and gives all SC participants access to data about goods and procedures (Centobelli et al., 2021).

Figure 8. Representation of typical circular SC reverse processes



Source: Centobelli et al., 2021

3.4.3.2 Internet of things

Introduction

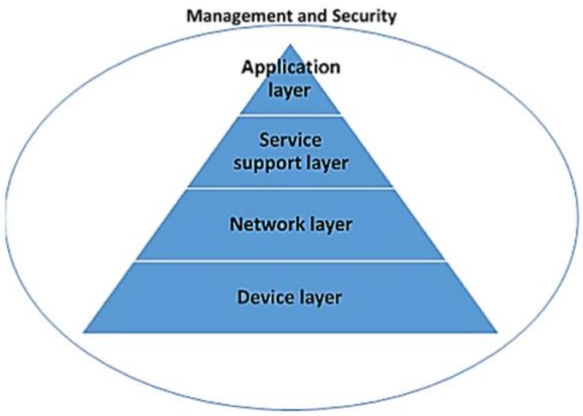
The IoT represents a novel paradigm that has revolutionized the concept of the Internet. It has transitioned us from a scenario of interconnected machines to one where objects are interconnected (Bouzembrak, Klüche, Gavai, & Marvin, 2019). IoT has brought about a fundamental shift in the way data is gathered and has expanded the Internet's scope, moving beyond the interconnection of computers to include any object capable of transmitting or receiving digital data. Consequently, IoT has the potential to serve as a substantial source of information (Bouzembrak, Klüche, Gavai, & Marvin, 2019).

Within smart environments, objects endowed with virtual identities and personalities operate through intelligent interfaces, facilitating connections and communication in diverse usage scenarios. These objects encompass a wide range of devices, such as smartphones, tablets, sensors, appliances, vehicles, cameras, RFID tags, drones, machinery, and more. An intrinsic feature of the IoT is its reliance on machine-to-machine (M2M) connectivity, operating independently of human intervention (Čolaković & Hadžialić, 2018). The application of IoT technology has directly impacted the advancement of traceability systems (Qian et al., 2020).

IoT architecture

The IoT architecture, as depicted in Figure 9 comprises several distinct layers (Bouzembrak, Klüche, Gavai, & Marvin, 2019)

Figure 9: IOT architecture



Source : Bouzembrak, Klüche, Gavai, & Marvin, 2019

Device Layer: This layer includes communication gateways and all devices that are placed in the environment. This comprises a variety of sensors (such as motion, light, temperature, and location sensors), devices that can send and receive data directly over a communication network or through gateways (such as transmitters and receptors), energy supply devices (such as solar panels and batteries), devices with multiple functionalities managed, and gateways. A vast array of pertinent wired and wireless communication technologies, including CAN bus, Wi-Fi, Bluetooth, Zigbee, and others, are also included in the Device Layer.

Network Layer: The vital task of enabling device data and the related protocol conversion to network layer protocols falls to the Network Layer. It offers connectivity, mobility support, authentication, authorization, and accounting, among other crucial network functions. This corresponds to the OSI (Open Systems Interconnection) protocol reference model's network and transport layers.

Service Support Layer: A variety of services are hosted at this layer to provide IoT services and applications. It includes features like data processing and storage in addition to specialized capabilities made for certain services and applications, all while considering the various needs of newly emerging services.

Application Layer: Situated at the top of the architecture, the Application Layer is where IoT applications and services are located. It serves as the driving force behind the core functionalities and features of the IoT architecture.

Management and Security: Management and security standard tasks like as configuration management, topology management, resource management, performance management, fault management, and account management are under the purview of this layer.

IoT and sustainable supply chain

Technologies including RFID, additive manufacturing, cyber-physical systems, and information and communication technology (ICT) play a major part in the field of IoT-enabled SC management (Samaranayake et al., 2022). For example, Boehmer et al., 2019 showed the extensive influence of IoT adoption on information exchange through an analysis of four thorough case studies. They stressed that manufacturers looking to take advantage of a wide range of commercial prospects can use IoT as a facilitator. In a similar vein, the integration of RFID technology with IoT adoption empowers members of the SC to access,

update, and exchange information promptly, thereby synchronizing existing data and product flows within the SC (Samaranayake et al., 2022).
IoT applications can be categorized based on their influence on broader society, with implications for economic value creation at both the enterprise and SC levels (Samaranayake et al., 2022).

Within the wider scope of SC management, the imperative to communicate information about the movement of goods is accentuated, particularly in the context of the increasingly globalized flow of goods (Samaranayake et al., 2022). Because of this feature, the SC industry presents an alluring opportunity for IoT adoption (Longo, Nicoletti, and Padovano, 2017). As a result, Industry 4.0 has been credited to IoT, which has the ability to transform traditional businesses into intelligent entities (Ali and Xie, 2021). Ben-Daya et al. (2019) have reported that the IoT has a significant impact on a range of SC operations, including reverse logistics and procurement. Moreover, the possibility of combining IoT with other technologies such as cloud computing and Big Data has the potential to start a digital revolution in the way the SC industry functions. Digital SCs have been proposed to benefit greatly from the IoT as an essential component and enabling technology (Samaranayake et al., 2022).
The significance of IoT in the logistics domain is further underscored by the advent of sensing devices that necessitate real-time connectivity and data exchange. The inherent potential of IoT lies in its capacity to establish connectivity between diverse systems and applications, thereby enhancing the efficacy of SC operations (Samaranayake et al., 2022).
According to Rebelo, Pereira, and Queiroz (2021), IoT can successfully handle the three core components of SC management: coordinated control, tracking, and monitoring.

3.4.3.3 Artificial Intelligence

Introduction

AI pertains to the examination of enabling computers to execute tasks of intellectual nature that, traditionally, were exclusive to human capabilities (Huang et al., 2018). In essence, it represents the capacity of machines or equipment to engage in cognitive processes, acquire

knowledge, and behave akin to human beings (Dhamija and Bag, 2020). AI encompasses any device or system that harnesses computational abilities to mimic human functions or replace human roles (Dhamija and Bag, 2020).
Professionals typically categorize AI into two broad domains: general AI (AGI) and narrow AI (ANI). AGI possesses the capability to execute tasks that are on par with or surpass human intelligence, while ANI specializes in performing specific functions (Bawack et al., 2019).

Over recent years, the development of AI has progressed swiftly, transforming societal dynamics. It has emerged as a pivotal strategy for nations worldwide, not only to enhance their global competitiveness but also to ensure national security (Zhang and Lu, 2021).

AI and sustainable supply chain
AI is capable of solving problems with remarkable speed and precision, even when dealing with extensive datasets. Presently, virtually every industry, and almost every sector of society, is deeply involved in digital applications (Klumpp & Zijm, 2019). Emerging trends aimed at fostering sustainability in business are closely intertwined with technological advancements, encompassing AI, robotics, big data, digitization, and the IoT (Sanders et al., 2019).

SC management stands out as one of the domains poised to reap substantial benefits from the evolving landscape of AI technologies (Belhadi et al., 2021). Nevertheless, despite the recent surge in research on this subject, the full extent of AI's potential in enhancing SCs remains largely unexplored. Given the intricate and uncertain nature of SC interactions, emerging technologies like AI hold promise in the development of synchronized SCs, where the collaborative sharing of information and resources yields mutual advantages (Dora et al., 2021).

The integration of AI into SC management facilitates the orchestration and optimization of network operations through several key functions, including: (i) revealing intricate behavioral patterns through multifaceted data analysis, such as classification, optimization, and clustering; (ii) sensing the surrounding environment to inform autonomous actions and proactively address emerging performance and quality issues; (iii) guiding SC design,

simulation, and planning; and (iv) enabling negotiation-based collaborative modeling (Toorajipour et al., 2021).

AI provides a notable benefit in terms of social sustainability, namely transparency, especially in the downstream parts of a SC. By using sophisticated data processing skills that can track the SC back to the sources of its raw materials, AI has the potential, for example, to educate consumers on how to make more educated purchasing decisions regarding commodities that are manufactured and supplied sustainably (Chidepatil et al., 2020).

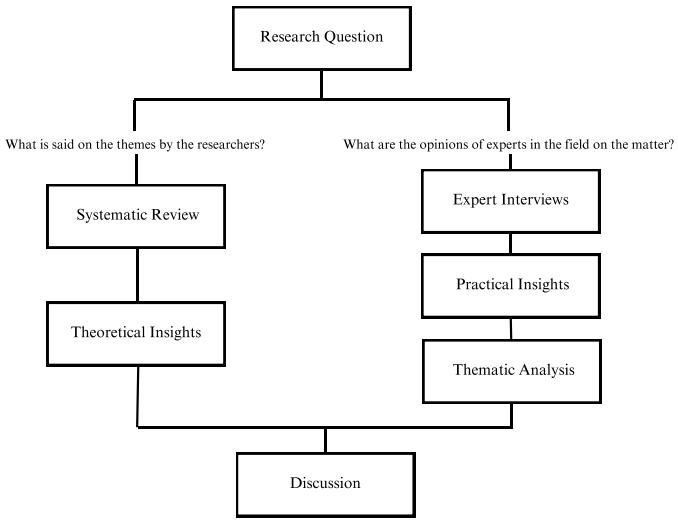
4 Research Design and Methods

In this chapter, the fundamental components of the research process are delineated, encompassing the research question, design, and contextual analysis. These constitute the foundation of any research endeavor, underscoring the significance of gaining a comprehensive understanding of the research environment. Following this, a thorough analysis of the data and methodologies used in the expert interviews and systematic literature research will be presented. The limits of the chosen methodology are acknowledged in the conclusion chapter.

4.1 Research strategy

The thesis addresses relatively novel topics concerning factual aspects associated with the transition to sustainability. An exploratory study method was required due to the innovative character of the new technology in this field. Ritchie et al. (2013) advocate for the use of qualitative approaches in investigating new phenomena within nascent knowledge domains. In alignment with this perspective, the research strategy employed adopts a qualitative approach, comprising a systematic review complemented by expert interviews (see Figure 10).

Figure 10: Research strategy



Source: Own representation

The purpose of employing two distinct yet complementary methodologies is to attain a comprehensive comprehension of the phenomenon under consideration.

The research methodology adopted in this thesis pursues two divergent avenues of knowledge exploration from an epistemological standpoint. The systematic literature review, on the one hand, has a positivist orientation. This viewpoint only accepts empirical, impartial, and scientific data (Armstrong, 2013). Conversely, field expert interviews help to shape field dynamics by providing insights from an interpretive perspective based on subjectivity that is dependent on context and time (Biggam, 2017). Therefore, by combining the two points of view, it is expected that the results will offer a clearer understanding of the role that Industry 4.0 technologies play in supporting traceability and the shift to a CE model in the plastics VC.

The incorporation of both methodologies allows the thesis to benefit from the advantages derived from both systematic review and semi-structured interviews. In particular, the investigated materials allude to a deductive approach because they rely on the work of earlier scholars, which is relevant if the systematic review's primary goal is to understand the academic perspective from an inductive stance. Similar occurrences are also revealed by expert interviews. The questions that guide the discussion are mostly inductive, but they also highlight a deductive approach and are related to the systematic literature review. Thus, this thesis attempts to understand the phenomenon or riddle in question and build upon previous research through the synthesis and iteration of these two methodologies.

4.2 Interviews data collection

According to Saunders et al. (2015), semi-structured interviews are among the most frequently used methods when it comes to qualitative research, this is because they offer a useful tool for acquiring valid and reliable data for the research questions.

Specifically, semi-structured interviews were used in this thesis as they were deemed more relevant for exploratory research, this method is often used when the interviewer is "aiming at gaining information about or exploring a specific field of action" (Döringer, 2021, p.265).

Therefore, considering what has just been said, this research adopts a qualitative analysis with semi-structured interviews with industry experts. Specifically, the reference sector

identified was the food and plastic packaging industry in general and the experts were selected to cover the various manufacturing states of the plastic VC.

Six interviews were conducted in February 2024, during the period from February 2 to February 16. The process for obtaining these interviews involved several contact methods directed toward experts in the field. The first interviewee was suggested by the supervisor of this thesis. Then a network effect was leveraged in which the interviewee suggested useful contacts to be interviewed. A total of 13 possible candidates were contacted through LinkedIn and traditional email retrieved from the company's website. From this set of contacts, only 6 agreed to be part of the interviews. Details on interviewee profiles and interview duration are given in Table 5

Table 5: Details on interviewee profiles and interview duration

Code	Organisation & Interviewee details				Interview	
	Sector	Country	Current Position	Years in the sector	Date	Length
P1	Food Distribution	Finland	Quality and Sustainability manager	25 Yrs.	2-Feb	49m33s
P2	Food Distribution	Finland	Manager IT Area Team Lead	5 Yrs.	5-Feb	38m30s
P3	Machinery Manufacturing	Finland	Technical and Sales Support	17 Yrs.	5-Feb	62m17s
P4	Food Distribution	Finland	Category Sourching Manage	23 Yrs.	9-Feb	49m53s
P5	Waste Management	Finland	Head Of IT	5 Yrs.	14-Feb	32m12s
P6	Manufacture of packing materials	Finland	Senior Marketing and Communication Specialist	6 Yrs.	16-Feb	25m41s

Source: Own representation

The semi-structured interviews conducted followed a well-defined strategy.
The entirety of the interviews was conducted in an online setting through Microsoft Teams. A total of 14 questions were posed to the interviewees (Appendix 1). The questions in all cases were preceded by a preamble that briefly explained the purpose of the study and requested permission to use the data collected during the interview to respect the interviewee's privacy.
The advantages of semi-structured interviews as a research methodology were exploited; in fact, the interviewer asked questions outside of the "list" in those cases where he deemed it necessary to elaborate on a concept highlighted by the interviewee.
In addition, in some cases, the interviewee requested in advance the questions that would be asked during the interview to better prepare for the actual interview.

4.2.1 Data analysis

As suggested in the book by Saunders et al. (2015) the interviews were transcribed and then analyzed.

The transcription of the interviews was automatically generated by the Microsoft Teams platform and was analyzed. Where necessary it was manually supplemented by reviewing the interview itself. In some cases, it was necessary to use external tools to transcribe the interviews, specifically Turboscribe.ai was used to transcribe the P5 interview.

As suggested by Saunders, M. et al. (2015) book, the transcript was reviewed immediately after the interview to have the concepts well in mind and possibly integrated into the transcript.

The transcripts were then imported to NVIVO qualitative analysis software by taking advantage of its 14-day free trial reserved for students. This software allowed in-depth analysis of the relevant themes.

The interviews were then coded (Appendix 2) following the principles of thematic analysis according to which the researcher codes the qualitative data in his possession to identify themes or patterns for further analysis, related to his research questions (Saunders et al. 2015).

The generated codes were therefore generated to fall under the specific research question. Specifically, 21 codes were collected for research question 1, 4 codes for sub-question 1, and 17 codes for research question 2.

4.3 Results

As analyzed in section 4.1, to analyze and segment the data collected from the interviews, a thematic analysis will be presented below. The themes that will follow will provide the basis for subsequently answering the research questions and sub-questions together with the data collected from the literature.

4.3.1 Integrated circular economy framework: plastic management and sustainable practices

Among the various themes extracted from the interviews, this is the one within which most of the codes found fall. The reason behind this may be due to an increased awareness of sustainable practices both by individuals themselves but also within organizations in general. The purpose of this Theme is precisely to go into the degree of awareness of sustainable practices undertaken by companies with a specific focus on plastics. The analysis also revealed an intricate relationship between Industry 4.0 technologies and the quest for a CE in plastics management.

Interviewees P1 and P4 base the narrative on their commitment to responsible plastic use. Their focus on using materials to their full potential and meticulous waste management underscores their dedication to circularity "We make sure we always manage our waste properly so that we can reuse it later" (P1). P1's view echoes a practical approach, emphasizing the key role of proper waste management in the CE journey. Respondent P4 on the other hand relies more on the effective recycling of materials by trying to find alternative methods for efficiently reusing them "CE essentially means finding the best alternatives for efficiently reusing materials" and also points to the importance of having a strategy to follow defining this as crucial "Having a strategy to follow is crucial and ensure that everyone is educated to follow it" this last consideration also aligns with another perspective of P6 who indicates how his position within his company involves precisely educating customers to make informed decisions about products, about their use and ultimately about proper recycling "our focus is on promoting a CE".

Respondent P2, on the other hand, representing another, more IT-oriented aspect of the industry, introduces the indispensable role of information systems in aligning with regulatory and environmental requirements. The concept of quantifying and categorizing plastics to achieve meaningful change underscores the importance of data-driven decision-making in sustainable practices. "By quantifying and categorizing the types and quantities of plastics," he explains, "we can initiate meaningful change." This ties in with what respondent P5, who works in the waste management industry, says, who points out that his company already has some technologies in place that, although still immature, can offer benefits, such as separating plastic by color for better recycling: "Currently in our operations

and facilities we have an advantage: our plastic can be separated into clear plastic and then colored plastic and black or brown plastic."
This fully incorporates what was said about Industry 4.0 applied to CE, namely the ability to leverage data to achieve strategic and sustainable results.

P3 offers a holistic perspective, emphasizing the symbiotic relationship between production processes and environmental impact. The commitment to maximizing material use and minimizing waste reflects a systems approach. "Whatever we acquire from the Earth," P3 notes, "we aim to give back or reuse." This encapsulates a CE mindset that goes beyond immediate commercial concerns to broader planetary impact.
P4's insights reveal a proactive attitude toward sustainability. The implementation of a bottle return system and clear guidelines demonstrates a commitment to reducing plastic use and actively engaging in initiatives that promote circularity. In addition, the mention of carbon negativity by 2025 and ambitious targets set the tone for a proactive attitude toward environmental responsibility.
P5 introduces the crucial perspective of raw material quality. The strategic importance of providing high-quality raw materials to outbound customers and the challenges associated with recognizing different types of plastics based on quality underscore the nuanced nature of CE implementation. This aligns with the general theme that achieving a CE involves not only quantity, but also attention to the quality of materials in circulation. The above also aligns with the insights of P5 which states their goal to maintain certain quality standards "We are dedicated to ensuring that our plastic solutions are not only environmentally friendly but also valuable".
To sum up, these interviews weave together the stories of professionals navigating the complex landscape of plastic material management in the context of Industry 4.0. These narratives collectively present a vision for a CE where plastic materials are not only managed but also intricately woven into a sustainable product that reverberates across industries and sectors. They range from the responsible management of raw materials to the data-driven decision-making process.

4.3.2 Technological integration in plastic industry – current practices, challenges, and future directions

This subject holds the second position in terms of the multitude of codes falling under its purview. The primary goal is to elucidate the contemporary state of the art along with the associated challenges and prospective directions pertinent to Industry 4.0 within the plastics industry.

Professionals affiliated with diverse organizations, spanning various echelons of the plastics VC, expounded upon their existing practices, revealing both simplicity and challenges. Respondent P2, an employee of a Food distribution company, articulated that "Our company engages in the purchase and distribution of products, serving as a central hub for plastics, with a primary focus on delivering food products," underscoring the pivotal role of information technology (IT). However, P2 also identified a gap in traceability: "We do not track packaging in our product." This limitation prompts inquiries about the visibility of plastics, shedding light on a potent" al area for enhancement in the current tracking mechanisms.

Contrastingly, respondents P4 and P6 delineated a form of internal monitoring, asserting, "In the present day, every material is meticulously monitored." This illustrates how, in certain instances, there may be a foundation for sharing information from plastic tracking among stakeholders in the VC. However, the lack of awareness regarding applicable technologies may impede this sharing. Consequently, it is noteworthy that several activities are still manually conducted, entailing time and associated risks. Respondent P6 remarked, "There are various methods through which we collect this information, but currently, much of this work is done manually".

The interviews consistently highlight gaps associated with technologies linked to plastic tracking, except for P5, who showcased cutting-edge technologies: "In our facilities, we have robotics and infrared cameras and use them to sort plastics based on their different properties." Although this industry, being at the end of the plastics VC, prioritizes technology for efficient sorting to obtain a superior recycled product, P5 also underscored the significance of obtaining additional data on the origin and composition of plastics for

optimal disposal “we would be able to more accurately pinpoint the plastic materials at each point of the VC, so that we would know what is the origin from the plastic. This forward-looking perspective accentuates the transformative potential of technology in waste management and recycling.

Optimism towards the future emerges as a recurring theme among all respondents. In some instances, this optimism centers on envisaging potential benefits from seamlessly integrating Industry 4.0 technologies into the plastics industry. For example, P3 expressed, “I believe there are opportunities to reduce plastic usage using Industry 4.0 technologies.” Others cited examples from existing practices, emphasizing the streamlining of processes through data analysis and contextual insights (P2; P4).

In the case of respondent P6, organizational goals include augmenting automation in operations. P6 articulated, “We are contemplating ways to enhance automation, exploring opportunities for utilizing activity and intelligence, making this a significant and ongoing focus.”

Collectively, insights suggest that while current practices may exhibit simplicity, the challenges lie in effectively tracking and tracing plastics. The reliance on manual efforts and the complexity of managing diverse materials signify the imperative need for more advanced and integrated solutions.

The prevailing optimistic outlook towards Industry 4.0 indicates that professionals acknowledge these technologies as pivotal to addressing current challenges. This internal consensus resonates with the transformative potential of technology to revolutionize the plastics industry, rendering it more circular and sustainable.

4.3.3 Enhancing supply chain dynamics – current practices and supply chain collaboration

The focus of this third theme is a detailed analysis of collaborative dynamics within the plastics industry. The interviewees, for the most part, expressed optimism about this

collaborative practice, envisioning potential benefits and anticipating challenges (P1, P2, P6).

As articulated by P2, there is a shared sentiment about the empowering nature of visibility in influencing systems and establishing requirements for a more transparent and manageable VC, particularly for side products like plastics. P2 notes, “This visibility would enable us to discern the types of materials, such as plastic or cardboard, involved in the process.” The interviewee emphasizes the significance of understanding the quality and types of plastic used, deeming it imperative given the diverse array of plastics present in a single product. Contrasting perspectives are offered by P3, who leans towards the need for a robust reporting system. P3 states, “We need some kind of reporting systems on how to make sure that we know what we’re buying. This also ties in closely with facilities and waste management services.” Both P3 and P1 highlight the current practice of seeking additional product information by directly asking suppliers or relying on established relationships of trust. P3 mentions, “I would have to ask from the company who made the product, and their system has to give these details for us.”

In a similar vein, P6 aligns with P4, emphasizing collaboration with partners who adhere to certifications. P6 notes, “We ensure that all our raw materials have certifications. This guarantees transparency for customers who wish to ask for information, and we strive to collaborate with partners who adhere to these certifications.” The reflections of P2 and P6 touch upon the potential challenges of increased collaboration, indicating that deeper collaboration might necessitate a broader discussion and substantial efforts, potentially resulting in a radical change in operations compared to the current practices.

Challenges are highlighted by P2 and P6 stating, “Effectively addressing this challenge demands a paradigm shift in thinking and the incorporation of new approaches involving diverse stakeholders.” This underscores the recognition that significant changes in operational paradigms may be required for successful collaboration in the industry.

In conclusion, the participants’ perspectives illuminate the interconnected nature of visibility, traceability, collaboration, and certification within the SC. This positioning of Industry 4.0 technologies as pivotal factors in advancing a CE for plastics reflects the evolving landscape and the challenges and opportunities presented by collaborative practices in the plastics industry.

4.3.4 EU regulations and ambitions in plastic and plastic packaging

Delving into the insights provided by plastics industry professionals, a recurring theme revolves around the profound impact of EU regulations and ambitions. The discourse mainly focuses on the criticality of adhering to food safety standards, as emphasized by P1, who emphatically stated, "The most important thing for us is food safety with plastics." This sentiment also reverberates in the narratives of P4 and P6, who, albeit in different words, emphasized the importance of ensuring the safety of plastic food contact products.

The complexities associated with compliance at the European level are made clear by P6, who perfectly captures the general sentiment of industry professionals, noting that compliance is a persistent challenge: "Whenever you do something at the European level, everyone has to comply and, of course, it's always challenging and it's a big hassle." This recognition reflects the complex and challenging nature of aligning with regulatory standards set by the European Union.

P2 also latches onto this complexity, shedding light on the growing focus on environmental impact reporting spurred by European legislation. This cultural shift toward more transparent reporting practices, especially in the plastics sector, indicates an increased industry awareness of the need for accountability in response to regulatory pressures.

Respondent P4 continues this theme by further deepening his understanding of industry dynamics, particularly regarding reporting challenges: "The complexity of having so many suppliers and so many types of products with different qualities makes reporting a bit chaotic today." Recognition of this chaos underscores the urgency of improving tools to effectively manage and track information.

A common thread throughout the discussions is the call for technological intervention. P4 summarized this need: "Regulations are becoming more stringent and we need tools to efficiently track and manage this information. Improving the tools is essential. Technology has the potential to be a valuable ally in addressing these challenges." This echoes industry recognition of the central role of technology in addressing the complexities of regulatory compliance and reporting requirements, thus promoting a more sustainable and circular approach to plastics.

4.3.5 Exploring the drivers to the change

This theme explores the drivers driving the transition to sustainable practices in the plastics industry, with a focus on the integration of Industry 4.0 technologies. Through thematic analysis of the interviews, distinct perspectives emerge, revealing a nuanced relationship between economic considerations, technological adoption, and regulatory dynamics. For convenience and greater schematization, the theme will be divided into subthemes into which participants' insights will flow.

- ***Tangible business case and clear strategy***

The first sub-theme is mainly supported by respondents P2 and P4, both of whom highlight pragmatic considerations that drive organizations to adopt sustainable practices. Participants emphasize the need for a tangible business case "Implementing sustainable practices generally requires a tangible business case. It is either driven by a specific customer request or by financial incentives that justify the investment" (P2). This emphasizes a pragmatic approach that aligns sustainability goals with economic viability. The interviewee also recalls the importance of all stakeholder involvement to make this transition truly happen, "While considerations such as positive public relations are significant, they alone may not be enough. Involvement of stakeholders who buy or sell, and adherence to potential government regulations, add weight to the case." Respondent P4, albeit more simplistically, states that one of the most important drivers is also to have a clear strategy in mind believing it to be critical.

The thoughts of the two respondents converge when it comes to optimism toward the future by putting the onus on regulations on the coming issue, "I think it will happen, and I think it is because of the regulations coming" (P2), and seeing technologies as essential drivers for change "Technology has the potential to be a valuable ally in addressing these challenges" (P4).

- ***Technology acceptance and adoption***

The second theme revolves around the acceptance and integration of Industry 4.0 technologies. Participants P3 and P4 envision a future in which a widespread understanding of these technologies will lead to their common use. This highlights a shift in mindset toward acceptance of technological advances for sustainable practices.

"As the understanding of this technology spreads, it will be more readily accepted and more commonly used" (P3). This suggests that technology, once perceived as a disruptive element, is gradually becoming an integral part of organizational strategies. The evolution of the technological landscape is not only recognized but is expected to be a norm in the near future.

- ***Shifting focus on product lifecycle***

The third topic reveals a significant shift in perspective, emphasizing a comprehensive product life cycle approach. Participants P4, P5, and P6 highlight the growing importance of considering the fate of a product after its use, with the goal of minimizing waste and emissions. This reflects a broader awareness of sustainability. "There is a shift toward considering what happens to the product after its use. It should become an integral part of our daily operations" (P4).

This shift in thinking signals a shift from a linear production model to a CE paradigm, in which products are evaluated for their entire life cycle, ranging from production to disposal to less obvious but still impactful aspects. Demonstrating this, respondent P6 talks about his company's commitment to reducing emissions, saying, "Our main goal is to incorporate green solutions that reduce emissions by at least 20 percent, and potentially more depending on the application."

These three sub-themes on drivers to change reveal interconnected motivations. On the one hand, purely economic and positive public relations considerations are intertwined with regulatory expectations; on the other, optimism about the transformative potential of technology is complemented by a broader awareness of sustainability throughout a product's life cycle. These interconnections result in an industry that, as we have seen in our study of the literature, is in strong transition, where sustainability is not only seen as a goal but as a kind of path driven by different motivations.

4.3.6 Exploring the challenges to the change

This theme in contrast to the one just described goes on to explore the difficulties and barriers related to integrating Industry 4.0 technologies to achieve circularity in plastics. Participants

highlighted several obstacles and uncertainties that will be, as in the case of the previous theme split into several subtopics.

- ***Lack of an immediate demand and business case***

A major challenge identified by participants is the absence of an immediate and compelling demand for addressing environmental issues (P2). This sentiment is echoed by the perception that sustainable practices require a tangible business case. The respondent pointed out that circularity initiatives may not align perfectly with existing operational approaches "The most significant challenge lies in the absence of an immediate and compelling demand to address environmental issues." Participant P5 also adds that the profitability aspect is not to be underestimated when it comes to making such economically impactful decisions as well "since we are operating in a commercial environment, then obviously we have to find a business case and make a profit from it." Participants stressed that benefits need to be articulated, even if they do not necessarily translate into immediate financial gains (P2, P5).

- ***Uncertainty and complexity in implementation***

Uncertainty surrounding the understanding of packaging materials and related aspects is a significant obstacle (P2). However, the respondent believes that although there may be initial complexity, creating visibility can be a starting point for addressing this challenge.

- ***Challenges in technology adoption***

The rapid development of Industry 4.0 technologies is perceived as a challenge, as potential customers need validation and reference before adopting these solutions (P3). "The reluctance to embrace these technologies immediately stems from the need for validation and reference." This reluctance and the need for a precursor to demonstrate successful integration further highlight this challenge.

- ***Need for comprehensive value chain integration***

Regarding plastic tracking technologies, participants stressed that effective solutions must cover the entire VC (P4). An enterprise-wide implementation is considered insufficient "Just one piece of the value chain is not enough […] it should cover the entire value chain, from the producer of the raw materials to the manufacturer and then to the customers" (P4).

- ***Challenges for system integration***

The challenge of determining the degree of autonomy of Industry 4.0 systems was highlighted, emphasizing the need for human oversight "The challenge lies in determining the extent of autonomy these systems possess. While they excel in certain tasks, they still require human oversight."(P6).

Challenges related to systems integration, risks of information leakage, and the competitive nature of the industry were also recognized (P6, P2).

"Whenever there is connectivity there is also risk of information leaking and these kinds of things or misinformation"(P6).

- ***Challenges for investments and maintenance***

In all the interviews conducted, emphasis was placed on the cost of integrating these Industry 4.0 technologies and the extra effort that these would provide "requires a lot of work, a lot of investment" (P4). Moreover, P5 has raised also the problem of the maintenance and the use of these systems, considering them relatively easy to adopt with some investment but difficult to maintain "It's easy to adopt, but then have the ability to maintain them or how to put them into use, that's the problem".

The findings suggest that overcoming barriers and challenges in implementing Industry 4.0 for plastics circularity requires a multi-faceted approach. From building compelling business cases to addressing uncertainties and ensuring comprehensive VC integration, participants' insights provide valuable guidance for navigating the complex landscape of Industry 4.0 in the context of the circular plastics economy.

4.3.7 IOT in Industry 4.0 - challenges, drivers in application and potential benefits

The landscape of Industry 4.0 implementation in the plastics industry unfolds with distinct voices and varied perspectives. The objective of this theme is to analyze existing applications for IoT technologies inside the interviewee companies.

Interviewee P1 describes the current absence of IoT in her company for plastic traceability but not at an absolute level, suggesting a spectrum of preparedness within the sector. On the other hand, P2's insights reveal a dichotomy in the approach to unit-level monitoring. While

RFID systems offer practical solutions for certain applications, concerns about the prohibitive costs of broader implementation reflect a sense of caution. Interviewee P2 also states that RFID sensors are currently inserted in their operations but not to facilitate the traceability of plastic “The closest we come to unit-level tracking is through RFID systems installed in the trolleys used for food delivery. This allows us to pinpoint the location of the trolleys within our warehouse and during transportation” Furthermore, interviewee P2, although not mentioning the sensors used, states that they are used within their company for temperature monitoring. Interviewee P5 also states how sensors for temperature monitoring are used in his company, also proposing a very interesting technology used in their factories to track products, but always only on an internal level: "infrared sensors for the temperature measuring. And then we have this machine vision for tracking the different articles on the production line” P5 therefore offers a glimpse into a multi-faceted integration of IoT into production lines, illustrating the role of technology in improving overall operational efficiency. This goes beyond cost considerations, positioning IoT as a tool for informed decision-making through real-time data collection.

A prevalent theme in the interviews is the careful consideration of costs associated with IoT. P2 highlights this by stating that although IoT offers benefits, the associated costs are significant. This financial apprehension appears to be a common thread running through the industry, reflecting a pragmatic attitude towards the adoption of Industry 4.0 technologies.
Interviewee P3 introduces the concept of adapting technology to material specifications, exemplified by the successful use of QR codes for stainless steel. However, when considering extending this technology to plastics, logistical challenges and hesitations emerge, highlighting the importance of adapting IoT solutions to the nuances of different materials “While this technology is effective for stainless steel, implementing it for plastics raises challenges”.
The integration of these IoT technologies into the plastics sector reflects a complex interplay between preparation, cost considerations, material-specific adaptations, and a forward-looking vision of sustainability. The sector appears to be at a crossroads, where decisions on technology adoption are influenced by both economic realities and a strategic vision for the future.

4.3.8 Blockchain in industry 4.0 - challenges, drivers in adoption and potential benefits

This represents the second theme addressing a specific technology, in this case, the examination of blockchain integration within Industry 4.0 for plastic circularity. The analysis reveals a diverse spectrum of opinions among industry professionals, with some expressing a lack of perception regarding the real value and potential benefits that this perhaps less-known technology could bring.

Interviewee P2, for example, highlights the absence of blockchain applications, underlining their prevalence in high-margin sectors such as wine. This observation raises skepticism about the relevance of the technology for plastic waste management, suggesting that economic considerations may prioritize other sectors over recycling initiatives. With this, he shows little propensity to adopt this technology, not perceiving its value. "I don't immediately perceive the necessity of integrating blockchain technology for management".
Interviewee P2 shows further skepticism by questioning the necessity and practicality of integrating blockchain into plastic recycling. This casts doubt on true innovation or practicality, indicating a desire for concrete evidence demonstrating the benefits of blockchain in the context of a CE for plastics.
Concerns about potential risks, such as system manipulation or incentives for dishonest practices, underline a cautious approach, underlining the need for ethical assessments before widespread adoption. The interviewee states that he could think about a possible application if dishonest practices were to start in this sector "It might be a consideration if there's a significant incentive for dishonest practices".
The majority of interviewees (P1, P3, P4, P6) are incapable of answering the questions relating to this technology "I don't understand the term blockchain technology" (P1, P3, P4, P6). This suggests potential knowledge gaps within the sector, reflecting a broader need for educational initiatives to improve understanding of the benefits and challenges of blockchain technology in plastic circularity. Interviewee P4, however, after a brief explanation by the interviewer on the possible applications of blockchain states: “We don't have this type of system yet, but it could certainly help us track which materials arrive and how they are used after the sale” while still showing enthusiasm in the event of adoption of the technology in question.

Interviewee P5 connects to this trend and, despite his skepticism, injects a note of optimism. While expressing skepticism about blockchain's immediate value, he recognizes its potential benefits. Information from the entire VC could enable more accurate estimates, improving transparency and environmental impact assessments. This reflects a positive perspective, recognizing the potential benefits of blockchain in optimizing material distribution and environmental assessments.

Finally, the different perspectives within the industry, ranging from cautious optimism to pessimism, highlight the complex factors related to blockchain integration for plastic circularity in Industry 4.0. The terrain is shaped by the following factors: economic priorities, concerns about dangers, gaps in knowledge, and hope for future gains. The effective incorporation of blockchain technology into the goal of a CE for plastics will depend on the industry's ability to analyze the pros and cons in a balanced way while addressing these divergent views.

4.3.9 AI in industry 4.0 challenges, future prospects and potential benefits

The examination of qualitative data pertaining to the subject matter "AI in Industry 4.0" offers a sophisticated viewpoint on the difficulties, opportunities, and possible advantages linked to the incorporation of AI in the plastics sector. Of all the topics associated with certain Industry 4.0 technologies, this one is undoubtedly the most popular and garners the greatest agreement. Contributors offer insightful observations that together create a clear picture of how AI may support sustainability and plastic circularity.

Interviewee P1 highlights a practical application of AI in the cold chain, suggesting the use of indicators to detect temperature variations “If the cold chain has been broken somewhere, maybe it could change color or something else, this could warn people that this has been in higher temperature than it should be” This intuition therefore sees AI as a significant support tool for controlling the quality of the product.
Another interviewee, P2, highlights operational considerations, expressing a preference for AI over other technologies due to its alignment with practical needs in managing additional information in plastic or packaging materials. The participant expects AI to be a more

streamlined and cost-effective approach compared to traditional methods. “I envision that employing AI in our industry could provide a more streamlined and cost-effective approach compared to traditional methods.” This sentiment is in tune with the overall goal of Industry 4.0: improving efficiency and reducing costs. This interviewee also places his hopes in a better recognition of the different types of plastics “One potential avenue could involve using AI to recognize various types of plastics. Perhaps utilizing a camera or similar technology, AI could interpret and classify the plastics, discerning their specific types”. This is in line with the broader vision of leveraging AI to improve operational processes and address challenges in material identification.

Critical viewpoints on the time restrictions related to manual analysis of big data sets are offered by interviewees P3 and P5. The understanding of P3, "Although it is easy to accumulate huge amounts of data... AI technology offers the opportunity to quickly analyze large data sets", this aspect regarding data analysis procedures is also echoed by interviewee P5 which states “Currently, we are not using it in manufacturing itself, we could use AI to process the data we have” suggests a latent potential for AI in optimizing production lines and improving outcomes for materials recyclable.

Interviewee P6 remains more cautious, providing a perspective on the dynamic nature of AI integration in the industry, stating: "Although these systems are not fully realized as true AI, human input is crucial for surveillance […] I think it's extremely interesting all the possibilities that AI offers." This quote highlights the evolving nature of AI applications and the continuous exploration of their capabilities.

Taken together, these insights describe AI as a versatile tool with the potential to address practical challenges, improve operational efficiency, and open up new possibilities in the plastics industry. Comments from participants not only provide a snapshot of the current state of AI adoption, but also suggest a dynamic and evolving landscape in which AI continues to shape the future of circularity in plastics.

5 Discussion and Conclusion

Previous chapters have presented the results of the study, exploring in detail the CE aspects of plastics, its SC, and how Industry 4.0 technologies can help in developing a useful tracking system for the transition to a CE. This last chapter presents a thorough analysis of the results, emphasizes the significance of the investigation, makes inferences from the data, and offers recommendations for additional research.

5.1 Discussion

This chapter aims to examine in detail the contributions from systematic research and those from qualitative research, the latter based on semi-structured interviews conducted with experts in the field. To articulate this discussion, an approach guided by the research questions that guided the investigative journey will be taken.

RQ1: What is the role of Industry 4.0 technologies in implementing Circular Economy principles in the plastics industry?

To explore the research question, we must examine the dynamic landscape of the packaging industry. This landscape is marked by challenges such as the surge in e-commerce, the demand for sustainable packaging, and stringent regulatory requirements. Emerging Industry 4.0 technologies are recognized as transformative forces in this context (WPO 2022). P4 and P6 respondents commonly perceive EU regulations as driving forces for change, emphasizing the importance of adhering to food safety standards and the need for technological interventions to meet regulatory compliance and reporting requirements. Specifically, Industry 4.0 plays a crucial role in addressing challenges related to incorporating recyclable plastics and promoting CE principles within the industry. This discussion delves into the intricacies of this dynamic relationship, highlighting the transformative potential of Industry 4.0 in reshaping the plastics industry towards CE principles.

The packaging industry strategically responds to environmental concerns, focusing on recyclable plastics, effective reporting systems, and end-customer education (Raheem, 2013) (P4; P6). However, the complexity of maintaining low contamination levels and identifying specific polymer types in recycled plastics presents significant challenges (Getor et al., 2020) (P2; P5). Achieving a CE requires systemic changes throughout the entire VC, going beyond efficient recycling techniques (Johansen et al., 2022). Respondents P2 and P6 align with this perspective, emphasizing the necessity for substantial organizational changes rather than individual efforts. P4 supports this view, stating that such changes are meaningful only if various stakeholders collectively move in the same direction. This is where the role of Industry 4.0 technologies becomes evident.

The integration of Industry 4.0 technologies in the plastics industry aligns with CE principles, addressing challenges across the VC. Literature and interview insights suggest that adopting these technologies, along with effective information sharing, enhances SC operations and contributes to operational excellence (Latan et al., 2018; Alkhuzaim et al., 2021). Interviewees express enthusiasm, proposing solutions to current problems and viewing the implementation of these technologies as a "facilitator" for transitioning to a CE. The digitization facilitated by Industry 4.0, as revealed in the literature and interviews, can provide timely operational and strategic information supporting CE goals.

A notable impact of Industry 4.0 on the plastics VC is the clustering of technologies, ranging from efficiency and automation to reducing raw material requirements through chemical recycling (Capetillo et al., 2022). Addressing challenges such as contaminants, polymer variability, and the need for collaboration among stakeholders becomes possible with the data exchange and automation capabilities offered by Industry 4.0.

The alignment of traceability with Industry 4.0 technologies is emphasized in CE efforts (Giovanardi et al., 2022). The integration of Blockchain, IoT, and AI promotes traceability along the entire plastics VC. This integration ensures order, transparency, and security by facilitating rapid information exchange and optimizing network operations in SC management. These technologies work synergistically to create a complete, interconnected system. A noteworthy challenge in this context is the participants' limited understanding of traceability issues; although this is a small sample, it is interesting to note that plastic

traceability was not considered a priority in the interviews conducted. Respondents say they have internal traceability and recognize the potential benefits of increased collaboration. At the same time, they recognize the need for shared perspectives among all stakeholders. Above all, there is an increased awareness that a compelling business case is critical. This case needs to demonstrate not only ecological benefits, but also economic benefits, to secure funding for any implementation of Industry 4.0 technology.

In summary, the investigation into the role of Industry 4.0 technologies in implementing CE principles within the plastics industry revealed a consistent trend in both literature and interviews.
This discussion underscores Industry 4.0's transformative potential, showcasing its ability to reshape the sector, address VC challenges, and advance sustainability goals. While meeting expectations, an unexpected finding emerged: interview participants displayed a limited understanding of traceability issues, suggesting a potential area for further investigation. This disparity may be attributed to the study's specific focus on Industry 4.0 technologies and the small sample size. However, contextualizing interview results reinforces the idea that Industry 4.0 can align industrial practices with environmental sustainability.

This dissertation contributes valuable insights into how Industry 4.0 technologies facilitate the plastics industry's transition towards CE principles. By emphasizing technology clusters, traceability, and the necessity for systemic organizational changes, our findings offer practical guidance for industry stakeholders, policymakers, and researchers striving to promote sustainability in the plastics sector.

Considering these insights, it becomes evident that adopting Industry 4.0 enables the plastics industry to effectively address challenges, enhance transparency, and progress towards CE, representing a positive stride in reducing waste and promoting resource efficiency. This comprehensive approach necessitates concerted efforts to align industrial practices with environmental responsibility.
While our study highlights the positive impact of Industry 4.0 technologies, it is critical to recognize the potential challenges and obstacles. The limited understanding of traceability issues among participants, despite technological possibilities, suggests the need for greater awareness and training in the industry. Furthermore, the recognition of a compelling

business case, encompassing both ecological and economic benefits, highlights the importance of aligning technological advances with tangible financial incentives. However, a more detailed analysis of the issue will be presented in the next paragraph.

In conclusion, our research affirms the pivotal role of Industry 4.0 technologies in reshaping the plastics industry towards circular economy principles. The knowledge gained contributes to the ongoing discourse on sustainable practices in the sector, emphasizing the necessity for collaborative efforts, organizational changes, and a comprehensive understanding of the ecological and economic benefits associated with technology implementation.

SQ1: What are the main drivers and barriers to the adoption and diffusion of Industry 4.0 to transition to a circular economy?

The literature review suggests several drivers for the adoption of Industry 4.0 technologies to transition to a CE. Firstly, there is growing pressure on manufacturers, both at international and local levels, to achieve sustainability objectives (Tang et al., 2022). The integration of Industry 4.0 technologies is seen as a means to enhance transparency, efficiency, and overall performance within the SC, aligning with the goals of the CE (Singh et al., 2021). The potential for cost-saving opportunities and long-term revenue benefits also acts as a driver for companies to adopt Industry 4.0 technologies (Latan et al., 2018).
The interviews conducted further clarify the drivers identified in the literature. A tangible business case and clear strategy emerge as critical factors, emphasizing the need for economic viability and stakeholder engagement. P2 and P4 interviewees emphasized the importance of specific customer demands and financial incentives, aligning with the economic drivers highlighted in the literature.
In addition, the interviews shed light on the role of regulations as a driving force for change. Participants express optimism about the impact of future regulations (P2), aligning with the literature's emphasis on international and local pressures for sustainability.
The focus on technology acceptance and adoption identified in the literature is corroborated by insights from P3 and P4, which envision a future in which Industry 4.0 technologies become an integral part of organizational strategies.
The literature's emphasis on the CE's goal of minimizing waste and promoting sustainability throughout a product's life cycle is echoed in respondents' discussions of the shift in focus

to the product life cycle. This shift in perspective aligns with the broader awareness of sustainability, as evidenced by P4, P5, and P6.

As far as the barriers are concerned, participants cite a lack of immediate demand, uncertainty, and challenges in technology adoption. The need for full VC integration, emphasized in the literature, is reiterated in the interviews.

The results suggest a nuanced relationship between the identified drivers and barriers, underscoring the complexity of adopting Industry 4.0 for the transition to a CE. While economic incentives and regulatory pressures drive adoption, challenges such as uncertainty, barriers to technology adoption, and the need for full integration pose significant obstacles.

In conclusion, our study emphasizes the intricate connections between motivations and challenges, offering a comprehensive understanding of the factors influencing the adoption and diffusion of Industry 4.0 technologies in the transition towards a CE. By integrating insights from both literature and interviews, we establish a robust foundation to guide industry stakeholders and policymakers through this transformative journey.

This phase of the research presented significant challenges for the writer, primarily stemming from a lack of literature on the subject. While the literature in other cases, as previously mentioned, was not exclusively focused on the plastics industry, it was even scarcer in this instance. Notably, there was a dearth of attention to the human perspective in the literature. While publications explored the functionality of Industry 4.0 technologies in supporting CE objectives, few delved into the opinions of individuals operating in this sector.

This thesis addresses this gap, providing a valuable contribution by offering a more complete overview of the drivers and difficulties in implementing this technology. It does so by taking a unique approach that shifts the focus from the technology itself to the ambitions and concerns of the individuals who will predominantly interact with these technologies. Consequently, our research provides a fresh perspective that considers the human dimension in grappling with the challenges and opportunities presented by Industry 4.0 technologies in the context of CE adoption.

RQ2: What are the key Industry 4.0 technologies that can be leveraged to implement a plastic recycling tracking system and how can they be implemented?

Again, to answer this second research question, we start from the literature and Interviews that shows us that the Key Industry 4.0 technologies identified for implementing a plastic recycling traceability system are those that foster data exchange and automation capabilities, qualities identified as critical to significantly improving circularity within the plastics VC (Capetillo et al., 2022). These technologies promise increased efficiency and productivity. They also offer the potential for improved reusability of materials and integration of diverse waste sources, aligning with contemporary policy dialogues on sustainability (Capetillo et al., 2022).

References by Capetillo et al. (2022) highlight the factors behind the incorporation of Industry 4.0 technologies, emphasizing social impact and opportunities for transparency and collaboration among stakeholders. Tang et al. (2022), Singh et al. (2021), and Rosa et al. (2019) further support these findings, emphasizing the role of Industry 4.0 technologies, such as data exchange and automation capabilities, in improving transparency, efficiency, and collaboration within the SC.

The literature highlighted two important Industry 4.0 technologies that play a key role in a plastic recycling tracking system: Blockchain technology and the IoT. Blockchain technology, known for its transparency, traceability, and real-time data access, acts as a decentralized transaction ecosystem, improving the visibility and efficiency of transactions in the SC (Nandi et al., 2021). IoT, through connectivity and real-time data exchange, facilitates coordinated tracking, monitoring, and control in SC management (Samaranayake et al., 2022; Rebelo, Pereira, and Queiroz, 2021). The incorporation of these technologies contributes significantly to the overall improvement of the CE in the context of plastic recycling.

The conducted interviews either corroborate what the literature supports or, in some instances, reveal a foundation of limited knowledge, especially concerning blockchain technology (P1, P3, P4, P6). These individuals assert their inability to answer the interviewer's questions due to their restricted understanding of the subject. Conversely, in certain cases, the interviews highlight the perceived unsuitability of blockchain technologies for the plastics sector. While acknowledging their potential to improve traceability and transparency, respondents believe they are less suitable for plastics and more apt for industries where fraudulent practices are more prevalent. Conversely, the discussion on IoT

devices exhibits more enthusiasm. Some respondents (P2, P3, P5) admit to using IoT devices in their operations, although they never specifically mention plastic traceability. Notably, P2 underscores the significant financial investment, reflecting a pragmatic industry stance towards technology adoption. For both technologies, interviewees do not emphasize aspects related to traceability. Nevertheless, this perspective might stem from a lack of awareness regarding the potential applications of these technologies for traceability and transparency in the plastics VC. In a specific example, a respondent sought a brief explanation from the interviewer about possible traceability applications, immediately recognizing its utility and expressing enthusiasm for future implementation.

Furthermore, AI emerges as a crucial technology that can synchronize SCs through multifaceted data analysis, environmental sensing, SC design guidance, and the possibility of negotiation-based collaborative models (Toorajipour et al., 2021). The examination of interviews unveils a more optimistic and widely embraced perspective on this technology. Interviewees share insights such as improved product quality control (P1), better alignment with the practical needs of the company (P2), and enhanced efficiency in data analysis (P3, P5). Despite the cautious sentiments expressed by P6 regarding human input, the prevailing consensus suggests that AI is a versatile tool capable of tackling practical challenges and shaping the future of plastic circularity. This diversification of Industry 4.0 technologies highlights the multifaceted approach required for the successful implementation of a plastic recycling tracking system.

Achieving a successful implementation of these technologies necessitates focused attention on data exchange, automation, and the seamless integration of Blockchain technology, IoT, and AI into the existing plastic VC. This entails adopting systems that enhance transparency and traceability, improve efficiency, and foster collaboration among stakeholders at every stage of the plastic VC, addressing challenges related to contaminants, various polymer types, and consumer perception (Capetillo et al., 2022).

In conclusion, the unexpected but insightful findings of this research highlight the complex interplay between industry perceptions and technological advances in the field of plastic recycling. Surprisingly, valuable insights were gained by interviewing individuals from various job positions, not just the tech ones. The discrepancy between the literature's

emphasis on the positive impacts of Industry 4.0 technologies and the reservations expressed in interviews, in the case of blockchain technology, highlights a communication gap between researchers and industry professionals. This requires a concerted effort to improve the dissemination of knowledge within the sector.

Looking ahead, the findings of this thesis have significant implications for future efforts in the field. As a researcher I was pleasantly surprised by the wealth of information obtained, realizing that these topics are actively discussed at all levels within companies. This prompts a call to action in the form of targeted educational initiatives and workshops aimed at demystifying Industry 4.0 technologies for a wider audience, ensuring a more informed and collaborative approach to their adoption in the plastics sector.
Furthermore, case studies and industry-specific examples that showcase successful implementations of Blockchain, IoT, and AI in plastic recycling can be useful. These real-world illustrations can serve as valuable tools for addressing misconceptions and hesitations expressed by industry professionals. Future research should focus on creating an archive of such case studies, providing tangible evidence of the transformative potential of these technologies.

Considering the broader impact of this thesis, it becomes evident that collaborative efforts between researchers, industry professionals, and policymakers are crucial to shaping the future of technological integration in the plastics value chain. This collaborative approach fosters a shared understanding of the benefits and challenges posed by Industry 4.0 technologies, laying the foundations for a more sustainable and circular approach to plastic waste management. Ultimately, the findings of this research contribute not only to current knowledge, but also serve as a catalyst for future actions to promote innovation, transparency, and efficiency in the plastics recycling sector.

5.2 Managerial and policy implications

This chapter will explore the managerial and policy implications arising from the in-depth study of literature and semi-structured interviews advocating not only technology adoption

but also a holistic approach that includes workforce development, collaborative initiatives, and strategic policymaking.

The Managerial implications gathered from this thesis underscore the need for companies to invest in the technology itself and workforce training programs that, as mentioned earlier, would be directly involved in change. Another piece relates to a gradual shift to a culture of continuous innovation, with strategic partnerships with suppliers of these technologies and collaborative initiatives aimed at maximizing the transformational potential of these technologies. In addition, key performance indicators (KPIs) specific to CE goals will be essential to measuring success.

On the policy front, many of the incentives for sustainability start from the policy institutions themselves. Therefore, these institutions are asked to play a proactive role in supporting the adoption of Industry 4.0. Such efforts could include refining regulatory frameworks to incentivize sustainable practices, allocating funds for research and development initiatives, making rational use of limited resources, and promoting international collaboration on standards and regulations.

In addition, education and awareness campaigns targeting industry professionals and the general public could serve as a demystifier for Industry 4.0 technologies.

Ultimately wanting to outline a roadmap for industry stakeholders and policymakers, this research accentuates the need for concerted efforts, continuous innovation, and collaborative structures to usher in a more sustainable and circular future for the plastics industry.

5.3 Limitations and suggestions

Like any research, these studies have specific limitations tied to the chosen research methodology. Saunders et al. (2015) highlight potential drawbacks of conducting qualitative studies with semi-structured interviews, such as the lack of standardization. When facts do not follow a predetermined pattern, concerns about reliability and dependency may arise. Denscombe (2017) contributes to this by discussing the "interviewer effect," which can influence both the responses given by the interviewee and the interpretation of those statements. To mitigate these issues, the interviewer strives to maintain a cautious and impartial tone that does not guide the interviewee's thoughts.

Another potential limitation is geographical barriers, impacting the variety of data and the interview setting. The interviews focused on a single state, Finland, possibly influencing results due to a narrow perspective. Additionally, conducting interviews online due to geographical constraints eliminates the empathetic relationship that in-person interviews might foster. Despite this, the interviewer attempted to approach the interviews as friendly conversations, disregarding specific time constraints. Furthermore, interviewees were assured about the privacy of their personal data, with a commitment to treating it with respect, maintaining anonymity, and avoiding disclosure of sensitive information.
In future research activities, it would be useful to delve deeper into the cognitive perspectives of additional states and end consumers as well as the study of other technologies that could also be useful for plastic traceability. This exploration could shed light on aspects such as consumers' willingness to pay a premium for products that provide better traceability. Furthermore, it would be very useful to undertake the task of conceptualizing a tracking system by providing a simulation that illustrates its practical functionality in a more tangible way.

The notion of conceptualization was contemplated by the author of the thesis. However, due to time and resource constraints, a theoretical approach was chosen rather than the initially planned practical simulation. Although the potential benefits of a practical simulation were recognized, the limitations forced us to adopt a more theoretical stance in completing the thesis.

5.4 Conclusions

This thesis aims to investigate the potential application of Industry 4.0 to the plastics industry sector aimed at greater traceability and transparency of its VC.
The analysis conducted was based on a qualitative methodology. A systematic search of existing literature on the topics of the CE of plastics and how to achieve this through the use of emerging Industry 4.0 technologies, and semi-structured interviews posed to industry experts who contributed their knowledge and expertise to the research.

As we conclude this exploration of the world of Industry 4.0 technologies and their significant impact, on bringing CE principles to the plastics industry several key insights and findings emerge. Through research and insightful interviews with industry experts we have gained a nuanced understanding of the potential and challenges associated with this paradigm shift revealing a path towards a more sustainable future.

The convergence of innovation and environmental responsibility witnessed in the plastics industry fills us with optimism. It is evident that Industry 4.0 not only tackles existing challenges but also fosters an ecosystem where stakeholders work together towards a common objective.

When reflecting on the impact of Industry 4.0 on the plastics industry, one is drawn to consider the responsibility that comes with technological advancements. This underscores the significance of implementing these changes in a manner that ensures the equitable distribution of benefits and addresses potential drawbacks with due diligence. This technological shift transcends being a mere industry trend; it symbolizes a collective commitment to a future where economic prosperity harmoniously coexists with sustainability.

The plastics industry stands at the threshold of an era, where Industry 4.0 serves as more than a buzzword but rather as a guiding principle, in achieving circularity.

The implementation of these technologies goes beyond being a business strategy; it signifies a dedication, to practices that go beyond the confines of a corporation.
Overall, this research expands the theoretical understanding of its field of research and provides theoretical implications for organizations seeking to promote more circular and transparent behaviors within their companies.

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Appendices

Appendix 1: Interview Protocol

Background Information	Please provide a brief overview of your role within your organization? - Company - Job position - Years in the industry and position
Understanding Current Practices	Considering the entire plastic value chain, what role do you play within this system?
	What do you understand by the term "circular economy"?
	What capabilities do you think your organization needs to successfully manage CE aspects?
	Please provide an overview of how plastics fits into your overall circular economy strategy and its role within your company's value chain.
	What technologies are used in your organization to track plastics along the value chain?
	Please explain any challenges or limitations you encounter with your current tracking systems .
Industry 4.0 Technologies	What are the potential applications and benefits of blockchain technology in plastic value chain tracking?
	How are IoT devices currently integrated into your plastics tracking operations?
	What role can AI play in tracking the plastics value chain?
Challenges and Concerns	From your perspective, what are the main challenges or concerns associated with adopting Industry 4.0 technologies for plastic tracking?
Future Perspectives	Looking ahead, how do you envision the future of plastic tracking with the integration of Industry 4.0 technologies?
	From your perspective, what benefits do you think proper integration of the above industries 4.0 technologies could lead to?

Appendix 2: Codebook

Research Questions	Main Code	Sub-code 1	Sub-code 2
RQ1:Plastic Industry and CE	Capabilities needed to manage CE aspects		
	Circluar economy		
	Circluar economy	EU regulations	
	Circluar economy	EU regulations	Reporting
	Circluar economy	IT relationship with CE	
	Plastic alternatives		
	Plastic industry		
	Plastic industry	Plastic analysis	
	Plastic industry	Plastic mix	
	Plastic recycling		
	Plastic usage		
	Plastic Value Chain Positioning		
	Supply Chain		
	Supply Chain	Current Practices	
	Supply Chain	Supply Chain Collaboration	
	Supply Chain	Supply Chain Collaboration	Needs
	Sustainable practices		
	Sustainable practices	Food contact plastic	
	Sustainable practices	Food contact plastic	Regulations
	Technology integration		
	Technology integration	Current practices	Challenges
SQ1: Driver and Barriers to Industry 4.0 transition	Barriers		
	Barriers	Possible Solutions	
	Driver		
RQ2: Industry 4.0 technologies for CE	Industry 4.0 technologies	Benefits	
	Industry 4.0 technologies	AI	
	Industry 4.0 technologies	AI	Challanges and limitations
	Industry 4.0 technologies	AI	Future prospectives
	Industry 4.0 technologies	AI	Possible benefits
	Industry 4.0 technologies	Blockchain	
	Industry 4.0 technologies	Blockchain	
	Industry 4.0 technologies	Blockchain	Challanges and limitation
	Industry 4.0 technologies	Blockchain	Drivers to the adoption
	Industry 4.0 technologies	IOT	Possible benefits
	Industry 4.0 technologies	IOT	
	Industry 4.0 technologies	IOT	Challanges and limitation
	Industry 4.0 technologies	IOT	Integration
	Industry 4.0 technologies		Challanges and limitation