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Circular Economy and Digital Supply Chain

The role of emerging technologies for facilitating sustainability

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ABSTRACT:

Increasing demand for sustainability and rapid digital technological development is changing how companies operate and manage their supply chains. This thesis investigates integrating digital technologies into supply chains to support the transition toward a circular economy (CE). The study mainly addresses how digital transformation helps to improve waste reduction, traceability, and transparency— the fundamental elements of circular economy objectives. This research emphasizes the application of emerging digital technologies or industry 4.0 technologies, including the Internet of Things (IoT), Artificial Intelligence (AI), blockchain, digital twins, big data analytics, cloud computing, and additive manufacturing.

A qualitative research methodology was adopted, applying a thematic analysis approach to explore patterns and insights within the data. Following Braun and Clarke's six-phase framework, the study systematically identified key themes relevant to the research objectives. Content analysis was then conducted using sustainability and annual reports from 18 multinational companies across various industries doing business operations in Finland. Through this method, five core themes emerged: the adoption of digital technologies, supply chain transparency, circular manufacturing integration, implementation challenges, and future directions for innovation.

Findings show that digital technologies improve supply chain functions and facilitate the implementation of circular economy practices more efficiently for businesses. Such digital technologies facilitate integration to enable real-time tracking, efficient use of resources, and development of closed-loop production systems. As per research, big companies have seen positive trends in adopting such technologies, but there are persistent challenges—financial, technical, regulatory, and organizational in nature. Small and medium-sized enterprise organizations (SMEs) are also negatively impacted, as they typically do not have the technical capability and the funds needed for digital transformation.

The research concludes that effective integration of digital technologies into supply chains is more than just the adoption of new technology. It requires coordinated planning to link technology and sustainability objectives, interdepartmental coordination, and supporting regulatory and policy environments. The findings emphasize that digital solutions must be embedded into the overall supply chain strategy to achieve meaningful circular economy outcomes. This thesis adds to an understanding of how digital technologies are currently being used in the industry by offering insights based on actual company practices. It also highlights the practical barriers and enablers influencing how organizations implement circular and digital strategies together.

KEYWORDS: Circular Economy, Digital Supply Chain, Emerging Technology, Sustainability

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Abbreviations

ABB	Asea Brown Boveri
AI	Artificial Intelligence
AM	Additive Manufacturing
BDA	Big Data Analytics
CE	Circular Economy
DfD	Design for Disassembly
DSC	Digital Supply Chain
DSCM	Digital Supply Chain Management

DSN	Digital Supply Network
DT	Digital Twin
EOL	End of Life
EPR	Extended Producer Responsibility
GPS	Global Positioning System
HRM	Human Resource Management
IoT	Internet of Things
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
MNCs	Multinational Corporations
NFC	Near Field Communication
QR	Quick Response (Code)
R&D	Research and Development
RFID	Radio-Frequency Identification
ROI	Return on Investment
SCM	Supply Chain Management
SDGs	Sustainable Development Goals
SMEs	Small and Medium-Sized Enterprises
SSCM	Sustainable Supply Chain Management

1 Introduction

The increasing pressure on global supply chains to be more sustainable has given the circular economy (CE), well-known as a promising concept emphasizing resource efficiency, waste minimization, and offering goods with a longer lifespan, significant momentum. Supply chains historically operated linearly: create, consume, and throw away. Eventually, in the context of food insecurity, material resource unavailability, and sustainability challenges of resources, this model has started to become unsustainable due to its negative environmental impacts, resource depletion, and incapacity to adapt to changing societal needs. (Agrawal et al., 2023) . This means that to overcome this overall present situation, the practices of CE are incorporated through recycling, remanufacturing, and repurposing during all stages of the product life cycle so that waste is minimized and the resource is used sustainably. Digital supply chains (DSCs) integrate emerging digital technologies to support seamless operations; thus, the transition to CE is being largely facilitated by DSCs (Dwivedi & Paul, 2022).

Blockchain, the Internet of Things (IoT), big data analytics, and other modern technologies are the leading digital tools to improve supply chain traceability, transparency, and coordination. Blockchain technology offers a safe, distributed approach to monitoring goods and resources throughout their lifetime. This enables different parties to exchange real-time information, fostering accountability and trust. Blockchain facilitates the view of how products and materials might be used rather than thrown away, consequently supporting circular economy objectives (Chaouni Benabdellah et al., 2023).

On the other hand, the industry 4.0 advancements, such as the Internet of Things (IoT), artificial intelligence (AI), and cloud computing, further reinforce the DSC's coherence with CE principles. Information from these technologies helps companies to make informed decisions as they crunch big data and predict the demand/supply variable, alongside optimizing the usage of resources while reducing waste. The IoT sensors can be used to measure the growth of stock levels and the flow of materials to ensure that the resources are being utilized efficiently and sustainably. For example. Predictive maintenance and demand forecasting, made possible by artificial intelligence (AI) and big data analytics (BDA), allow supply chains to minimize unplanned downtimes, which, in turn, supports longer product lifespans and low resource consumption, which are key objectives of a circular economy (L. Liu et al., 2023)

Furthermore, integrating circular economy (CE) ideas with digital supply chains (DSCs) is progressively seen as necessary for reaching sustainability and resilience in modern companies. Empowered by new technologies and the acceptance of digital technologies, digital supply chains enable stakeholders to share knowledge and cooperate, allowing companies to create flexible and sustainable supply chain systems. Organizations can match CE objectives using DSC capabilities to guarantee long-term sustainability, lower environmental footprints, and improve resource economy. However, effective implementation depends on overcoming obstacles, including skill gaps, infrastructure problems, and stakeholder involvement, which call for strategic investment and leadership support. For companies, the convergence of CE strategies and digital technologies offers transforming possibilities for reaching sustainability and improving competitiveness and operational performance over time. (Arenkov et al., 2019; Santiago et al., 2024; Altan et al., 2024; Benabdellah et al., 2023)

Moreover, it is crucial to learn from the past how digital supply chains (DSCs) increase supply chains' agility and resilience under worldwide events like the COVID-19 epidemic. By supporting circularity, resilience, and sustainability in manufacturing and distribution networks, DSCs help lessen the effects of such events. (Agrawal et al., 2023). Through encouraging cooperation and using CE models, DSCs play vital roles in enabling an organization to solve conventional supply chain issues, including limited resources management, environmental impact reduction, and operational performance enhancement. (Dwivedi & Paul, 2022).

Particularly in cybersecurity, coordinating the objectives of digital supply chains (DSCs) with circular economy (CE) goals presents many difficulties. Kaur et al. (2024) highlight how more vulnerabilities in linked supply chains result from the growing reliance on digital technologies. Usually aiming at shared digital environments, cyberattacks may disrupt operations, result in financial losses, and pilfer intellectual property. The lack of coordinated efforts among supply chain partners to handle cybersecurity issues aggravates these risks. Smaller supply chain providers, with limited resources to commit to cybersecurity, could become weak points in the system and give attackers access to more prominent networked companies. Dealing with these hazards requires large cybersecurity expenditures and cooperative frameworks to improve resilience in digital supply chains. (Kaur et al., 2024).

As Agrawal et al. (2023) stated, a second significant problem is the existence of both technological and process-related obstacles to using digital technologies for CE operations. Limited standardization, inadequate infrastructure, and a mismatch between CE principles and Industry 4.0 technologies all help prevent the integration of digital tools into supply chains. Along with these difficulties, financial constraints, including high initial investment costs and the lack of efficient economic incentive systems, prevent companies from adopting digital-enabled CE practices. Furthermore, institutional and regulatory gaps, including unclear policies and weak government support, are confusing companies trying to match their supply chains with CE objectives. Overcoming these obstacles requires smart investments, skill development, and strong policy creation. (Agrawal et al., 2023).

1.1 Research gap

Although extensive research exists on the principles of the circular economy (CE) and the concept of digital supply chains (DSC), there is a gap in the combined literature. It remains underexplored how emerging technologies like IoT, blockchain, and AI can collectively support CE strategies within supply chains. The current literature lacks comprehensive frameworks or models demonstrating how these technologies can work together to resolve CE issues.

Although much literature addresses the possibilities of digital technologies concerning CE objectives, research highlighting the actual industrial application of digital technologies has not been given enough attention. For instance, little is documented around more specific insights into the role of digital twins, additive manufacturing, or cloud computing in sectors like manufacturing, commerce, or logistics in enabling the CE. This creates a gap in understanding how these technologies can be practically implemented, scaled across diverse industrial settings, and, most importantly, contribute to sustainability.

Research has been conducted to highlight the benefits of adopting digital technologies for CE; however, there is much less research on the challenges and barriers to this integration faced by companies. Concerns such as data security, interoperability, cost implications, and the absence of skilled personnel are regularly published but rarely examined in detail. In addition, how companies can overcome these obstacles to enjoy the advantages of digital supply chain technologies is still mostly unknown.

Digital technologies, particularly emerging technologies, have not been well measured or investigated for their effects on sustainability outcomes, including traceability, waste reduction, and openness. There is a lack of empirical evidence and measures on how newly developed technologies directly assist in CE objectives. Given this lack of quantifiable results, companies find it challenging to evaluate efforts at supply chain digital transformation.

There is a lack of empirical evidence and metrics that assess how emerging technologies directly contribute to CE goals. This lack of quantifiable results prevents organizations from determining the success of digital transformation initiatives within their supply chains. Though several frameworks on digital transformation or CE already exist, an overall actionable framework specifically designed for integrating digital supply chains with CE strategies is still lacking. It should address technology adoption, process redesign, stakeholder collaboration, and sustainability measurement. This gap has limited organizations' ability to transition effectively to digitally enabled circular supply chains.

1.2 Aim of the research

This study aims to develop a broad insight into the relationship between the circular economy and the digital transformation of supply chains. How emerging technologies help to facilitate better sustainability outcomes through supply chain management. This research will help in finding the practical and strategic means to sustainable parts of supply chain operations by questioning how the digitization of parts of supply chains, such as Internet of Things (IoT), blockchain, Artificial Intelligence (AI), digital twin, cloud computing, additive manufacturing, etc., can support the transition required from linear practice to circular practice. Thus, the following research question is addressed accordingly.

1. What are the key opportunities and challenges in implementing digital supply chain technologies, and how can these technologies be integrated to achieve circular economy goals?

This research addresses three areas of enabling CE strategies by integrating digital technologies inside supply chains. Combined, the questions provide comprehensive insight into the status, the integration process, and associated challenges and opportunities. The research question referred to the present status of industries pursuing digital supply chains toward the goals of a circular economy transition for the company. The investigation will look into what is happening today within organizations' practices, challenges, and preparedness regarding the adoption of circularity by digital technologies. This question will analyze existing gaps within supply chain models and study how firms currently address problems related to resource efficiency, waste management, and sustainability.

The research question also explores the opportunities and difficulties of using digital supply chain technologies to assist CE strategies. This includes finding potential obstacles, such as technical compatibility, financial and organizational issues, regulatory issues, and data privacy concerns. This research also explores the benefits, including enhanced efficiency, decreased environmental impact, and improved collaboration among stakeholders. By addressing these opportunities and challenges, this research aims to provide practical insights that help companies overcome barriers and make the most of new technologies for circular economy success.

Moreover, this research question also addresses how emerging digital technologies can be included in supply chains to improve the sustainability of outcomes. This study looks at how new technologies like IoT, blockchain, AI, digital twins, cloud computing, additive manufacturing, and big data analytics could be used to ensure supply chain operations align with CE principles. This will help one better grasp how these technologies might be used to improve transparency, maximize resource economy, and enable closed-loop systems for recycling and reuse.

This thesis focuses on one of the most critical problems in modern industry and the environment: circular economy strategies enabled through digital supply chains and how emerging technologies help allow sustainability. Since it offers a possible paradigm to improve resource efficiency, minimize residuals, and extend product lifetime, a circular economy (CE) is growingly appealing. Nonetheless, applying CE strategies calls for a careful review of organizational supply chains enabled by digital technology to ensure the seamless operation of the process.

Using blockchain, IoT, and big data analytics in digital technologies enhances operational efficiency by raising traceability and openness all around the supply chain. These features let companies better track resource flows across their networks, reduce environmental effects, and create closed-loop recycling and reuse systems. This addresses the unsustainable practices worldwide and fills a critical gap in how businesses operate today. This research investigates how emerging technologies can serve as enablers to overcome traditional circular economy barriers, such as reverse logistics, tracking limited materials, and integrating sustainability practices at every stage of the supply chain.

In the present industrial era, it is essential to drive technological innovation in supply chains that align with the circular economy's principles. Industries currently encountering resource scarcity, environmental degradation, and escalating consumer demands for transparency have the potential to significantly address these challenges through the implementation of advanced digital approaches. In addition to facilitating the transition to a circular economy, digital technologies facilitate resource management, operational efficiency, and closer collaboration among all stakeholders in a company's supply chain. This investigation aims to determine the degree to which emerging technologies can be implemented to convert conventional supply chains into sustainable and resilient systems to the increasing digitalization of supply chains.

This research suggests the necessity of a concise, actionable framework that any organization can use to meet the demands of aligning digital technologies with the circular economy. Indeed, a successful transition to such a model faces significant challenges, from technological interoperability and data privacy to considerable implementation costs. This study presents practical insights for organizations by analyzing established best practices and emerging innovations. These will form the foundation for developing scalable and adaptable solutions that satisfy organizational objectives and global sustainability standards. This will, therefore, help bridge gaps between theoretical advances and practical applications and make the study relevant in academia and industry. This will allow a gap to be identified, and individuals will be aware of the organization's current state in Finland and how it can be integrated into companies that want to achieve circular economy goals. To achieve this aim, the following specific objectives are outlined.

1. To examine the role of digital technologies in promoting circular economy efforts within the supply chain.
2. To analyze the impact of digital technology on key sustainability issues such as information transparency, traceability, and waste reduction
3. To define a best practice for organizations transitioning through digitally transforming their supply chains to implement a circular economy.

These three primary objectives focus on different but essential parts of integrating circular economy strategies through digital supply chains. The first objective is to examine how emerging digital technologies like the Internet of Things (IoT), blockchain, artificial intelligence (AI), digital twin, big data, cloud computing, and additive manufacturing can help progress circular economy efforts. To do this, need to give priority to examining how these technologies help optimize resources, manage their lifecycles, and reduce waste.

The second objective is to evaluate the influence of these emerging digital technologies on critical sustainability concerns, including waste reduction, traceability, and information transparency. By addressing these issues, this objective aims to illustrate the potential of emerging technological solutions to reduce traditional barriers to sustainability and provide actionable insights into their applications in supply chain networks.

The third objective is to establish best practices for organizations to transform their supply chains through digital transformation. To achieve this goal, a comprehensive strategy to address technological, operational, and organizational adversities, including a roadmap to improve circular economy strategies to make them both efficient and effective, must be developed and implemented.

1.3 Limitations of the study

This research uses a qualitative approach, meaning it examines corporate sustainability reports and industry documents instead of using numbers, statistics, or real-time data. This method helps to deeply understand how companies describe their sustainability efforts, digital adoption, and future goals. However, it does not measure the actual impact of these technologies in real-world operations. As a result, the findings may be based more on what companies report about themselves rather than what is happening in their supply chains. There is also a chance that companies present their efforts in a more positive light, which could create a reporting bias. This research relies on secondary data sources, including sustainability reports, company statements, and annual reports, rather than direct feedback from industry professionals. Even though these reports offer valuable insights into company strategies for sustainability and digital transformation, they help understand broad industry trends. However, they might not discover the hidden challenges, gaps in implementation, or the detailed decision-making processes behind these initiatives. In that case, a mixed-methods approach, incorporating interviews, surveys, or case studies, could provide a more holistic understanding of the real-world application of digital and circular economy strategies.

The study includes 18 multinational companies operating in Finland. These selected companies specialize in manufacturing, logistics, energy, technology, and packaging, among other fields. Even though the categories of businesses in this sample come from various industries, the findings might not apply universally, especially to smaller firms or local supply chains. Big companies usually possess better economic resources and technological progress, which might not represent the challenges and opportunities encountered by small companies since they typically do not release annual or sustainability reports. Corporate sustainability reports are publicly available and self-declared documents from the companies, which might reflect corporate sustainability branding instead of the actual operations of the industry. There is a clear potential that businesses can concentrate on successful digital projects without encountering difficulties, unsuccessful projects, or regulatory non-compliance. This research acknowledges the presence of potential selective disclosure bias, which can influence perceived success in digital and circular economy transformation.

Applications of AI, IoT, blockchain, cloud computing, big data analytics, digital twins, and additive manufacturing in supply chains are evolving at a fast pace. Thus, the findings of this study can be utilized only for digital transformation in the years 2022–2023. Any upcoming technological change, policies, and sustainability processes may impact the adoption of digital technology; hence, research is always needed. It can be altered through technological progress, policymaking, the adoption of sustainability processes, and long-term adoption dynamics.

2 Theoretical framework

2.1 Circular economy

A methodical approach to economic development, the Circular Economy (CE) acknowledges the reciprocal advantages among companies, society, and the environment. In contrast to the linear economy, which runs under a "take, make, dispose" paradigm, this is in line. Instead, the CE emphasizes the need for a circular system that maximizes material cycles and reduces waste by optimizing resource use. Therefore, the circular model guarantees constant use of resources by including elements like long life cycles, simplicity of maintenance, repair, reuse, remanufacturing, refurbishing, and recycling. (Kurniawan et al., 2022; Payer et al., 2024).

Aiming to maximize resource use efficiency, the systemic and regenerative Circular Economy (CE) is a tool for economic development. CE encourages the use of perpetual resources, unlike the traditional linear model. The basic ideas of Circular Economy (CE) are extending the initial use cycle, enabling secondary use by repairs and resale, and recovering materials for reintegration into the manufacturing processes. Cooperation among stakeholders—including companies, governments, and consumers—improves environmental sustainability while advancing social and economic benefits. (Lehmacher, 2017).

CE has been defined and characterized through various principles across academic and practical fields. According to (Kurniawan et al., 2022), CE aims to optimize resources associated with products and materials throughout their life cycle and, as such, is encompassed by deep resource management that minimizes environmental externality. (Payer et al., 2024) With the pillars of sustainability—environmental, economic, and social through digital innovation and strategic governance. The CE model aims to create regenerative economic practices regarding ecological resilience and decrease the need for virgin resource inputs (Zekhnini et al., 2022).

According to Lahti et al. (2018), the circular economy has recently attracted considerable interest in achieving sustainable development. Often referred to as the circular economy, this economic model aims to reduce waste while simultaneously maximizing resource reuse and recycling. This approach contrasts with the conventional linear "take-make-dispose" model, which has resulted in the depletion of natural resources and the accumulation of waste.

Furthermore, academics and professionals agree that the circular economy is a timely and highly relevant issue since industries should broaden their attention beyond the interests of their shareholders and take care of more general society and environmental issues. Using virgin resources more effectively across the shift to a more sustainable production and consumption pattern involving businesses and all stakeholders helps the circular economy aim to decouple economic growth from their use. (Cheng & Chou, 2018).

In addition, the difference between a linear and circular economy is mainly in the product life cycle. A linear economy follows a traditional take-make-dispose model, while a circular economy applies the 3R strategy (reduce, reuse, recycle) to prevent resource depletion and waste generation (Noman et al., 2022). A circular economy is an industrial economy intended to be restorative or regenerative by intention and design. (Ranta & Saari, 2019).

Therefore, the circular economy is now seen as an important and timely topic since scientists and practitioners demand that companies go beyond the interests of shareholders and pay attention to broader economic and environmental issues. It aims to decouple economic growth from virgin resource use by ensuring sustainable production and consumption systems involving enterprises and all stakeholders that enable more efficient use (Geissdoerfer et al., 2017).

The circular economy (CE) concept represents a disruptive paradigm change from linear production-consumption to a regenerative and sustainable system. It covers procedures that extend a product's life cycle and lower environmental impact. It calls for a complete transformation in corporate activities, policies, and societal behavior, combining social, ecological, and economic aspects. This approach, evident in many sectors, including the energy, building, and agri-food sectors, seeks to maintain resource value, reduce greenhouse gas emissions, and promote ecological balance. (Raimo et al., 2023).

The circular economy is critical in modern business practices, serving as a framework for sustainable growth, focusing on resource optimization and waste minimization. Let's take a closer look, especially in e-commerce. Implementing all data analytics and methods improves internal processes and significantly contributes to customer satisfaction, which means that they are adopting the key targets of the circular economy. Analytics helps prevent businesses from creating problems by optimizing resources and minimizing waste, making operations more sustainable (Seyi-Lande et al., 2024).

In addition, technology companies can use Big Data to optimize their processes and become agile, allowing them to evolve rapidly to meet the market's demands. Enhancing efficiency helps create the foundation for sustainable business models at the heart of the circular economy. This agility, enabled by Big Data, guarantees business resilience as well as less environmental impact (Simpson et al., 2024).

This also highlights the need for data governance systems that effectively control data privacy and security concerns in environmental research. By carefully handling personal information, these systems support the efficient acceptance of circular economy ideas and help build trust. By ensuring data integrity and transparency, one can inculcate sustainable practices that combine social responsibility with the environment in companies and research (Layode et al., 2024).

2.2 Digital supply chains: an overview

The digital supply chain is the network through which digital processes and data are incorporated in all procurement, manufacturing, distribution, and customer interaction phases. Such a system lets data be compiled and examined immediately, improving the visibility and control of the supply chain (Dolgui & Ivanov, 2022). Recent research has attempted to define digital supply chains by their end-to-end connectivity, which helps companies to adapt in the face of changes and base decisions on data instead of estimations (Bag et al., 2023).

Moreover, digital supply chain (DSC) is a relatively recent concept that evolved in response to modern supply networks' growing complexity and globalization. By contrast, digital supply chains benefit from applying advanced technologies to enhance supply chain operations' efficiency, transparency, and environmental sustainability. Emerging technologies, including big data analytics, the Internet of Things (IoT), 5G, artificial intelligence (AI), blockchain, and digital twins, each of which helps differently to build an agile and information-based supply chain, enable this transformation. (Kamble et al., 2022).

The digital transformation of supply chains has lately attracted considerable attention. Businesses want to improve operational efficiency, responsiveness, and resilience in an increasingly complex and unpredictable corporate environment. Defining a digital supply chain as integrating and optimizing supply chain processes through the strategic application of digital technologies, including cloud computing, the Internet of Things, big data analytics, and blockchain, is not complex. (Ageron et al., 2020a; Büyüközkan & Göçer, 2018; Marmolejo-Saucedo & Hartmann, 2020).

The data-driven attribute of digital supply chains enables the optimization of the entire supply chain with improved configuration and decision-making (Tran-Dang & Kim, 2021). The new digital supply chains are more connected, data-driven, and responsive than traditional linear supply chains; management experts consider them a competitive advantage in the global economy because they allow enterprises to create sustainable value while increasing customer service (Ageron et al., 2020).

New-age supply chains driven by technology, data, and interconnectivity are digital supply chains. They use emerging technologies, including Big Data, cloud computing, the Internet of Things (IoT), robotics, and artificial intelligence (AI) to improve supply chain efficiency, flexibility, and sustainability. A technology-driven framework identified as digital supply chain management (DSCM) lets companies combine operations, use resources, and react fast to unpredictable market demand. (Agrawal & Narain, 2018).

According to Agrawal and Narain (2018), digitization in supply chain management has become an imperative rather than an option in the present globalized market. Digitized supply chains increase visibility and transparency across levels, from procurement to delivery, reduce inefficiencies, and improve decision-making. An organization capable of allowing real-time monitoring and management of resources, thus reducing wastage, will align with the circular economy principles, incorporating technologies like cloud-based platforms, sensors, and data analytics.

Digital supply chains are essential to pursuing sustainability objectives, including lower environmental impact and resource optimization, in the circular economy framework. IoT technologies let a company track goods throughout their lifetime for remanufacturing, recycling, and reuse. Big Data analytics supports predictive insights concurrently that enable businesses to maximize inventory and logistics while reducing risks. (Agrawal & Narain, 2018).

Digital supply chain (DSC) is a big transition from traditional supply chain design. It integrates advanced digital technologies to connect processes, minimize inefficiencies, and make better decisions. In a broader sense, DSC refers to implementing Big Data analytics, Cloud Computing, the Internet of Things (IoT), Blockchain-based tools, and digital infrastructure to build an integrated and responsive play (Ageron et al., 2020).

This contributes to agility and integration across supply chains while enabling the transparency necessary at the organizational level to maintain sustainable performance.

In theory, the DSC translates this linear chain into an interconnected digital solution, otherwise known as a digital supply network (DSN), which aligns with systems thinking and dynamic capabilities. Key advantages of applying such a networked approach relate to timely data transfer, visibility of material in transit, reduction of bullwhip effects, and accuracy of decision-making aligned to targets such as cost-efficiency, agility, and responsiveness (Ageron et al., 2020). This is not just about manufacturing but also about using digital technologies to optimize design processes, collaborating with suppliers and logistics, and contributing to economic, social, and environmental sustainability.

Besides, recent IoT and Artificial Intelligence technologies allow performance monitoring in real-time and predictive analytics. For instance, Big Data analytics carves visibility and resilience in decision-making, while cloud-based systems create an avenue for better supply chain integration and responsiveness. This digital space has forced organizations to look at supply chain aspirations: while integrating digital tools, projects can be managed effectively without compromising clean energy and overall sustainability (Kamble et al., 2021).

On the one hand, DSC equally promises much and faces serious challenges related to adopting technologies, competency gaps, and business model best practices. Digital transformation requires organizations to revise their job profiles and give them competency in different aspects, starting with data analytics and leadership skills (Ageron et al., 2020).

2.3 Digital technologies in the context of digital supply chains

Industry 4.0 is also known as the Fourth Industrial Revolution. This has gained a lot of support in recent years. It refers to a huge shift in how businesses and industries work. Industry 4.0 uses emerging digital technologies in production and industry, such as digital twins, the Internet of Things (IoT), cloud computing, and big data analytics (Kazancoglu et al., 2023; Shi et al., 2020). The technologies change not only the way industries work but also how they are designed, how long they last, and how competitive they are. Digital technologies are crucial for change in supply chains and the circular economy. They make things easier to track, allow it to make decisions based on data, and help to build closed-loop processes. The goal is to save as many resources as possible and minimize as little as possible. According to Zimmermann et al. (2024), digital technologies can be classified into three main groups: enablers, integrators, and application technologies.

The foundation for connection and data processing is built by digital technology enablers. For examples, the Internet of Things (IoT), which enables devices to communicate with each other and be monitored in real-time; big data analytics, which help companies find useful information in large, complex data sets; and cloud computing, which gives companies scalable, collaborative tools to store and share data across the supply chain. These technologies allow the individuals within the supply chain to view each other and collaborate more efficiently, increasing responsiveness and sustainability in operations (George et al., 2014; Marston et al., 2011; Zhou et al., 2020).

Integrators of digital technologies, such as artificial intelligence (AI), simulation tools, and cyber-physical systems, act as the analytical and automation core of digital supply chains. AI facilitates predictive maintenance, automated decision-making, and personalized services, while simulation technologies help optimize production planning and resource allocation. Cyber-physical systems link digital and physical components through feedback loops, enabling real-time control and intelligent process adaptation across the value chain (Wamba et al., 2020; Szozda, 2017).

Application technologies are those technologies that are applied directly in the operational environment. Additive manufacturing (3D printing), with on-demand and material-efficient production, is one of them. Robotics and autonomous systems, with improved accuracy and speed of operations, and human-machine interface technologies like augmented and virtual reality for enhanced safety and training of employees, are other examples. These technologies enable circularity by minimizing material loss, allowing product customization, and prolonging product lifecycles through sophisticated repair and refurbishment capacity (Ford & Despeisse, 2016; Lu, 2017).

This thesis analyzes digital technologies as central pillars supporting the transition from traditional to digital supply chains through digital technologies that help achieve a circular economy. The study examines how integrating enablers, integrators, and application technologies helps organizations address challenges. Such as poor visibility, inefficient reverse logistics, and limited stakeholder coordination—barriers that have traditionally hindered circular economy adoption. Technologies like blockchain and digital twins further support this transformation by enhancing transparency, ensuring data integrity, and enabling real-time optimization of supply chain processes (Saberi et al., 2019; Kritzinger et al., 2018). This thesis investigates how companies deploy these digital solutions across various industries; this research provides practical insights into the role of digital technologies in advancing supply chain models in digital forms, which pave the way to achieve a circular economy. The findings contribute to a growing body of knowledge demonstrating how Industry 4.0 technologies are catalysts for operational efficiency and critical drivers of sustainability and long-term resilience in global supply networks.

2.4 The intersection of CE & digital SCM

Digital technologies will enable companies to develop new value propositions and business models, guiding the way to a circular economy. For example, digital platforms can allow product-service systems that let businesses offer access to goods instead of selling them, promoting the design of long-lived, easily repairable products. Furthermore, one can monitor the whole supply chain process.

The effects of the COVID-19 pandemic have further emphasized the significant role digital technologies play in finding solutions for circular economy strategies communicated among supply chain units. On the other hand, pandemic disruptions shifted attention toward supply chain resilience and agility as firms consider options to improve their capacity for unexpected demand or supply shocks. Digital technologies, especially in this context, have helped companies better monitor and react to demand over supply (J. Liu et al., 2022).

Circular Economy (CE) ideas introduced through Digital Supply Chains (DSC) indicate the beginning of sustainable, closed-loop systems aiming at waste reduction, better use of our limited resources, and operational efficiency. Remanufactured, recycled, and reused resources in a CE (Circular Economy) model help to extend the lifetime of goods or materials while lowering environmental damage. These objectives rely on having the correct tools and knowledge to monitor events in real time, assess data, and automate tasks. When applied all through supply chains, digital technologies enable resource tracking, waste reduction, and recovery techniques. DSC and CE develop a comprehensive, global strategy focusing on social, financial, and environmental objectives. Practical application of digital transformation increases supply chain visibility and efficiency. Furthermore, it is flexible enough to support sustainable practices aligned with world sustainability targets, such as the Sustainable Development Goals (SDGs) (Kurniawan et al., 2022).

2.5 Emerging technologies in supporting CE in SCM

Emerging technologies are necessary to meet circular economy objectives throughout the supply chain. Digital Supply chains (DSCs) relate to using a range of digital technologies to enable access and sharing of real-time information among supply chain stakeholders, leading to real-time operational decision-making. They facilitate a better flow of goods, increase visibility, and ensure traceability, simplifying the process of implementing closed-loop systems — a building block for CE. Digitizing the supply chain will enable organizations to reuse, recycle, and reduce resources so that operations align with environmental sustainability objectives (Agrawal et al., 2023; Dwivedi & Paul, 2022).

Digital technologies significantly improve circular economy (CE) practices and support their potential to promote sustainable resource use, waste minimization, and supply chain resilience within SCM. Technologies such as digital twins, blockchain, big data analytics, and artificial intelligence (AI) provide access to real-time accurate information and will fundamentally change the linear model of production and consumption into a circular economy system, where recycling processes are monitored for efficiency trails with technologies like additive manufacturing; cloud computing features help maintain customer satisfaction during service-based product transformation through mechanisms enabling reduction in energy consumption by balancing the resource loads throughout business supply chains using intelligent decision-making systems (Preut et al., 2021).

The Internet of Things (IoT) is a revolutionary technology that provides real-time tracking and monitoring of resources within supply chains. Fitting into the circular economy (CE) paradigm helps solve a lot of pain points, such as ineffectiveness, waste, and lack of supply chain visibility that traditionally plague supply chains. Combining IoT and CE ideas effectively lets companies lower resource consumption, increase transparency, and support environmental sustainability. IoT plays a significant part in connecting tangible life to the virtual worlds, enabling the digital transformation of industrial systems through the Internet of Things (IoT) and establishing the relationship between IoT and CE since IoT technologies enable data-driven decision-making to reinforce CE objectives, including reducing, reusing, and recycling. (Kazancoglu et al., 2023).

IoT is fundamentally a system of interconnected equipment that automatically gathers, analyzes, and distributes data. Among these devices are sensors, RFID tags, smart tags, NFC, QR codes, GPS systems, blockchain, and cloud computing, all of which help create an ecosystem of real-time information flows that allow supply chain players to maximize operations and reduce environmental impact as it is seen in figure 1. (Taj et al., 2023). Taiwanese organizations explored some areas of IoT being driven by CE strategies within organizations, specifically highlighting how IoT technologies can facilitate closed-loop supply chains, in which a business seeks to reduce waste disposal as well as environmental harm by reusing or recycling resources involved in production (Rusch et al., 2022).

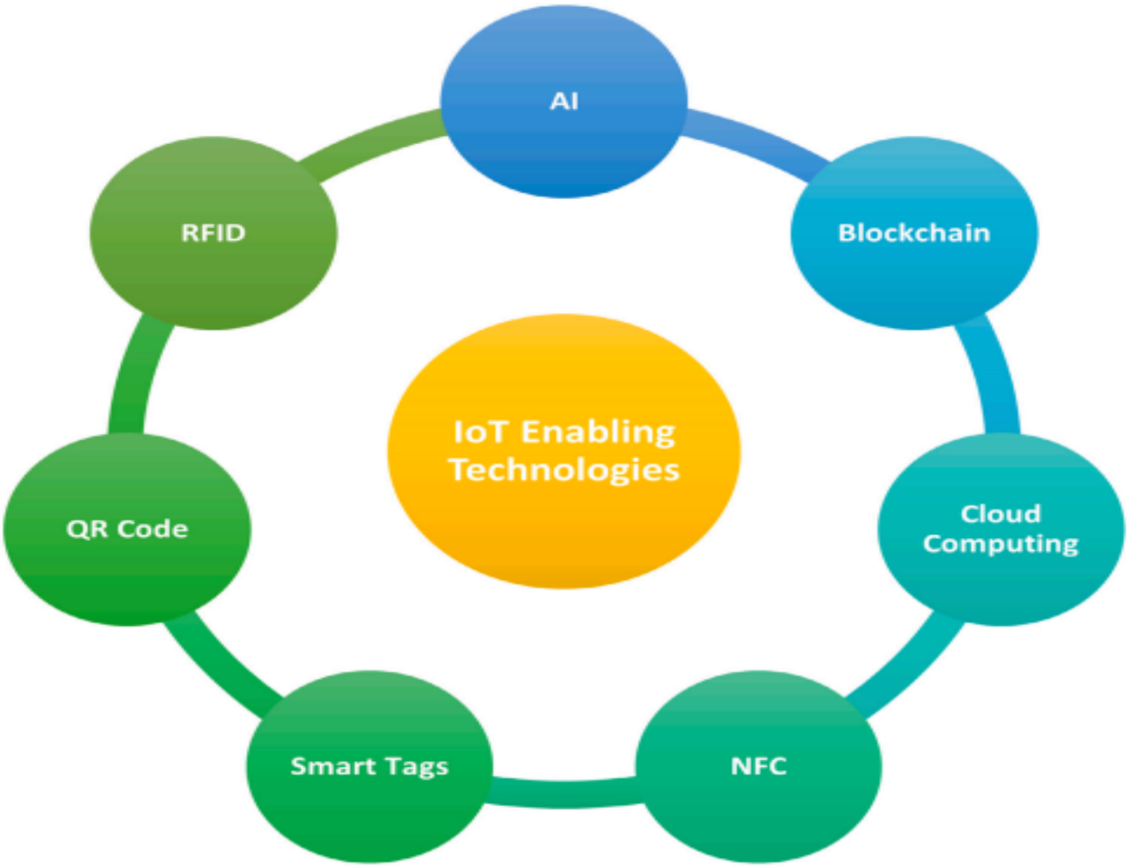

Figure 1. Main technologies used for IoT-based SCM research (Taj et al., 2023).

IoT is a more robust and holistic real-time tracking platform capable of tracing the location and movement of materials, parts, and products, providing information regarding the status at any time. Its ability aligns with CE principles based on resource efficiency and environmental care (Benabdellah et al., 2023). Using the Internet of Things, businesses can monitor their inventory levels in real time, consequently allowing them to manage their inventory levels optimally. RFID tags and sensors that organizations deploy alongside their operations create an ecosystem that will enable them to do things such as track inventory status, identify bottlenecks in supply chains, and a plethora of other IoT use cases. This has rendered CE an essential weapon for the prevention of overproduction, storage cost cuts, and the minimization of resource wastage (Kazancoglu et al., 2023).

As part of the circular economy, reverse logistics is a fundamental component for recovering, recycling, and reusing materials. The Internet of Things (IoT) enables this process in a digital supply chain by directly tracing returned products, components, and materials. Returned items are equipped with sensors to provide IoT-enabled real-time product condition data, allowing companies to determine if the items can be recycled, remanufactured, or repaired. These seamless connections between IoT and the digital supply chain optimizations resource utilization support various efficiencies and sustainable practices (Rusch et al., 2022).

The Internet of Things (IoT) enhances visibility and control over product lifecycles in digital supply chains and the circular economy by embedding sensors that track usage patterns, environmental conditions, and wear from production to disposal or repurposing (Payer et al., 2024). IoT supports predictive maintenance, extends asset life, and lowers resource waste by notifying businesses of maintenance needs before failures using real-time data. IoT sensors track important manufacturing performance factors, preventing unplanned depreciation and maximizing efficiency. Companies can determine whether goods can be rebuilt, remanufactured, or recycled at the end of their lifetime using these insights inside a circular economy framework (Yadav et al., 2020). IoT-enabled tracking systems improve material traceability even more, guaranteeing adequate and safe recycling and letting companies keep responsibility outside the point of sale, including regulatory compliance and circular economy ideas. IoT integrated into the digital supply chain through optimal lifecycle management helps organizations streamline reverse logistics, improve resource recovery, and enable sustainability (Yadav et al., 2020).

Sustainability requires leveraging **Artificial intelligence (AI)** to advance digital supply chains that combine circular economy concepts. By extending material lifetime, reducing waste generation, and optimizing resource use efficiency, such approaches help support the world's environmental goals. Real-time tracking and process optimization driven by AI can help ease this shift. Better sustainability and resilience in the supply chain around circular economy concepts can result from AI-led predictive maintenance and optimization of digital supply chain operations.

According to Shahin et al. (2024), artificial intelligence improves efficiency, automation, and decision-making in many sectors. Similarly, optimization of demand planning, supply chain management, and maintenance prediction driven by artificial intelligence guarantees efficient resource allocation and minimization of disturbance. Better human-machine interaction supported by speech recognition helps to improve voice-activated equipment operation, safety compliance, and automated transcription of logistics documentation. From fault detection in manufacturing lines to resource allocation, customer segmentation, and sentiment analysis for business data-driven decisions in supply chain optimization, the classification algorithms support Using drones to lower waste and increase visibility in supply chain operations, help object detection support automation in manufacturing and logistics using quality inspection, medical imaging, and environmental monitoring. Therefore, regression analysis is absolutely indispensable in quality control, financial analysis, and price optimization for companies to make predictive adjustments in market trends and inventory management. Predictive analytics will also support supplier performance evaluation, yield prediction, and traffic demand forecasting to enable proactive decisions meant to lower risks and improve efficiency in transportation and logistics. The integration of artificial intelligence in the digital supply chain offers resilience, agility, and sustainability-building capability through end-to-end visibility, real-time monitoring, and predictive insights (see Figure 2).

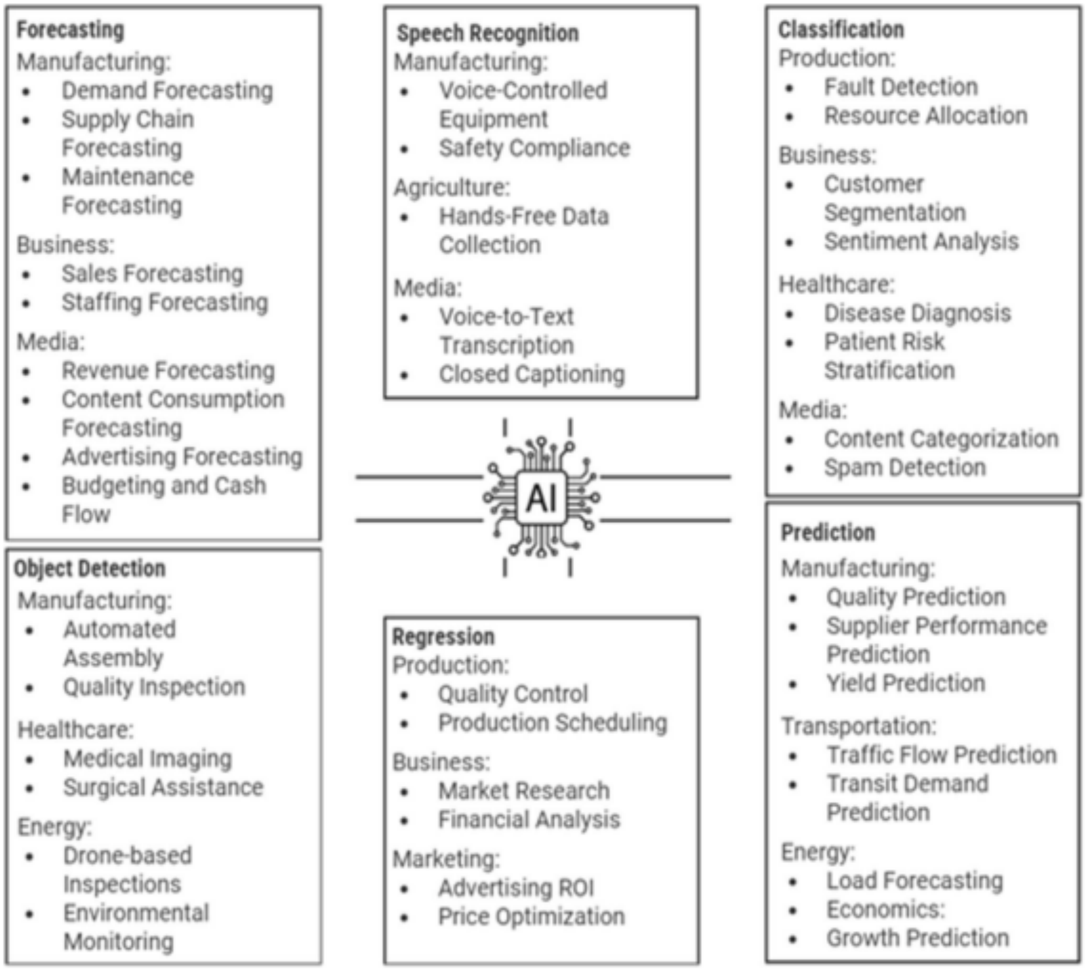

Figure 2. Application of AI (Shahin et al., 2024)

Across the board, artificial intelligence technologies can increase operational productivity, lower costs, and even advance environmental sustainability in some sectors. Through artificial intelligence-driven systems in manufacturing, smart factories enable automated production, intelligent scheduling, and predictive maintenance, enhancing operational efficiency while reducing costs and environmental effects (Gao & Feng, 2023). Beyond manufacturing, artificial intelligence has revolutionized logistics and transportation, streamlining inventory control, ordering processing, and network design. Removing unnecessary transportation and logistics inefficiencies, these developments help to save energy and lower emissions while increasing supply chain efficiency (Zhong et al., 2024).

One of the most exciting applications of artificial intelligence to further environmentally friendly digital supply chains is predictive maintenance. Organizations can manage enormous volumes of real-time data with artificial intelligence (AI) to enable predictive modeling, which then forecasts, for example, equipment failure events, enabling optimal asset use and preventive maintenance. In addition to extending the lifetime of equipment and lowering the need for resource-intensive replacements, it lessens the possibility of unplanned downtime and the energy and material waste that follow from unneeded, emergency replacements. Constantly observing equipment conditions, artificial intelligence systems examine parameters including temperature, pressure, vibration, and energy consumption. Any deviations from normal running conditions are noted, and a quick response is called for. Artificial intelligence-powered monitoring systems find component wear and tear in manufacturing, enabling proactive repairs. (Plathottam et al., 2023).

AI usage in digital supply chains can also help with green manufacturing and environmental sustainability. Direct AI-driven predictive analysis finds the best production schedules, logistics, and resources required to reduce waste and the energy necessary for every manufacturing process without compromising productivity. Cheaper and more efficient solutions go hand-in-hand with the circular economy principles of reducing waste and saving resources (Cioffi et al., 2020). AI systems can also validate the environmental performance of supply chain actions to combat greenwashing by analyzing big data sets related to energy consumption, CO2 output, and sustainability statements. Increasing transparency and credibility, discouraging opportunism (Dauvergne, 2020).

Artificial intelligence can present significant benefits for digital supply chains, particularly for improving testing, logistics, and microservices along the networks. Predictive analytics, for instance, can guide inventory decisions that lower waste and energy consumption;

meanwhile, route optimization driven by artificial intelligence can help lower fuel consumption and emissions on the logistics side. These features coincide with the circular economy (CE) ideas, facilitating environmental stewardship and sustainable resources. By forecasting demand, optimizing Inventory levels, and simplifying transportation paths, artificial intelligence also helps companies maximize efficiency and reduce their environmental impact. (Plathottam et al., 2023).

The industrial applications of blockchain and other emerging technologies across various sectors have attracted increasing attention from researchers, engineers, and practitioners. **Blockchain Technology**, which features visibility, transparency, relationship management, and innovative contracting, contributes positively to circular economy practices. Multiple intermediaries and trust or performance issues often characterize traditional supply chain activities. The power of blockchain can be used to disrupt supply chain workings for enhanced performance, distributed governance, and process automation(Chang & Chen, 2020).

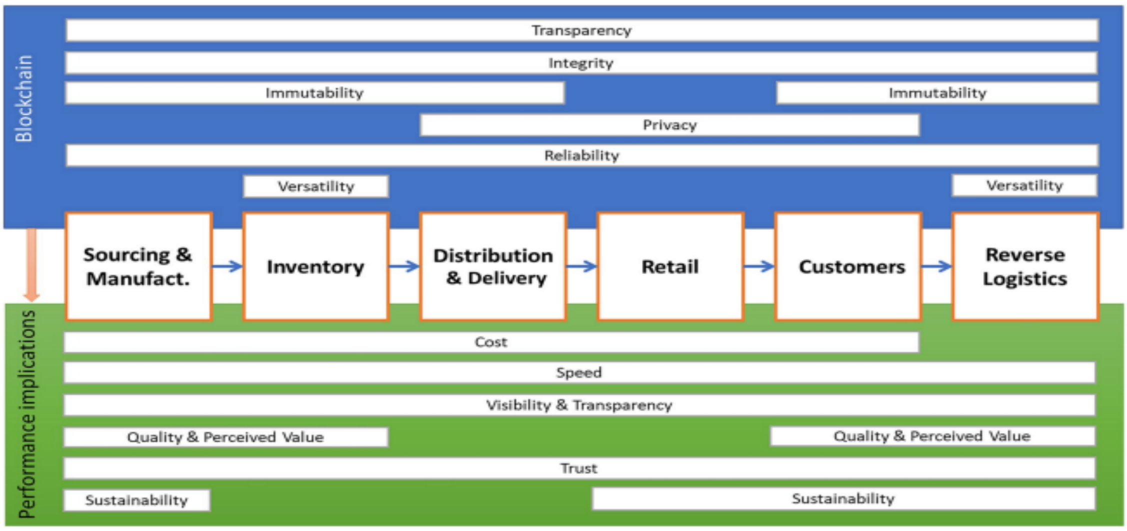

Figure 3. A theoretical framework for blockchain implementation (Difrancesco et al., 2023)

Figure 3 outlines how blockchain's technical features—transparency, integrity, immutability, privacy, reliability, and versatility directly enhance key supply chain processes (sourcing, inventory, distribution, retail, customer experience, reverse logistics) to improve performance outcomes like cost efficiency, speed, visibility &transparency quality & perceived value, and sustainability.

Blockchain's transparency and immutability of all transactions logged provide extra advantages, particularly in supply chains. This would help to explicitly trace raw materials from source to distribution, encourage ethical procurement, and reduce counterfeit products. This guarantees that sensitive corporate data is kept while allowing sharing with stakeholders and providing blockchain privacy and dependability. This flexibility allows them to integrate IoT and AI in their supply chain operations. Blockchain will improve supply chain performance, from sourcing and manufacturing to inventory management, distribution, retail, and reverse logistics. Companies can also track real-time product lifecycles to reduce resource use and unnecessary inefficiencies. Blockchain will enable companies to deal with the returns, recycling, and remanufacturing in reverse logistics—an essential aspect of a circular economy. Real-time insight helps organizations reduce waste, recover resources, and optimize inventory. (Difrancesco et al., 2023).

From a sustainability perspective, blockchain technology might completely transform the supply chain. According to Munir et al. (2022), Blockchain will guarantee suitable traceability, enhance visibility through information sharing, increase transparency for the process, and decentralize the whole structure, improving the supply chain's economic sustainability. Moreover, it can also lead to environmental and social sustainability through resource efficiency, accountability, smart contracts, trust building, and reducing fraud (Friedman & Ormiston, 2021).

Blockchain technology provides great potential for enabling transparency and traceability in supply chain activities, thus facilitating the circular economy (Chauhan et al., 2022). The ability to immutably and decentralizedly record data allows for precise tracking of materials, products, and resources in the supply chain (Payer et al. 2024). On the other hand, automated smart contracts add more value to this technology by streamlining various supply chain operations, including payments, logistics, and inventory management, thus accelerating adoption while reducing waste. Blockchain can also enable stakeholders— suppliers, consumers, and recyclers—to work seamlessly, improving coordination among the players engaged in a circular economy project (Caldarelli, 2024). Through blockchain implementation in supply chain management, companies can leverage its possibilities to boost transparency, traceability, and process automation, supporting circular economy goals around the supply chain ecosystem. (Liu et al., 2023).

This combination of advanced industry practices and blockchain technology can move industries and companies toward achieving the goals of a circular economy. Through the combination of technical factors, the recent findings articulate the improvement of intra- and inter-links of the supply chain with technical aspects, enlightening blockchain with economic, environmental, and social components of its materialization within the folds of supply chain sustainability (Upadhyay et al., 2021). Blockchain drives economic sustainability by bestowing effective traceability, improved visibility using shared information, greater transparency, and decentralization in the process. At the same time, it promotes environmental and social sustainability through resource efficiency, accountability, trust building, and fraud deterrence, all of which are pivotal elements for circular economy practices (Chelh & Ababou, 2023).

Even though many sectors are worried about including the circular economy with sustainability, social responsibility, and financial development, blockchain technology provides safe, tamper-proof, and permanent data storage options, supporting the fundamental ideas of transparency and traceability across digital supply chains. Combining blockchain technology with circular economy projects gives businesses tools to increase visibility and streamline supply chains while including sustainable practices around the value chain. Using efficient accountability systems, companies monitor the materials in use, transit, and upcycling phases and their consumption and responsible usage, enabling the actual circular supply chain (Munir et al., 2022).

These blockchain-based technologies are expected to become the standard in many industries, tracing and spreading information related to products. In this respect, the more recent review on blockchain applications in the supply chain contains an interesting statement: "The discourse regarding sustainability appears rather limited compared to other subthemes" (Köhler et al., 2021). This, therefore, implies that the application of blockchain in supply chains is an issue that has received much attention in academic literature, but using the technology to unlock sustainability gains is an area yet to be plowed (Yadav et al., 2023).

The journey towards a circular economy is challenging for organizations that are aware of beneficial changes in resource management and synchronization with multiple entities (Gupta et al., 2018). However, recent advances in digital supply chain technologies and **Big Data Analytics** integration have emerged as transformational enablers of the circular economy. This helps companies make ethical, data-driven decisions by embracing circularity and inspiring cooperation with supply chain individuals.

Big data analytics can help companies moderate the application of circular economy strategies, providing excellent social, environmental, and economic results (Giudice et al., 2020). The company uses thorough and varied data sets to reveal essential insights into resource use, waste minimization, and material flow optimization within the supply chain. Predictive analytics, for example, can spot consumption abnormalities and inefficiencies in materials, allowing proactive actions to maximize resource recovery and lower waste. Businesses must link data and supply chain operations to maximize circular economy flows by including data-driven insights into running operations and strategies.

Developing a circular economy that drives economic growth calls for cooperation among all those involved in the supply chain and open communication about their activities. Big data analytics helps digital supply chains operate as a platform for stakeholders to exchange data, jointly commit to sustainability goals, and work on innovation. This kind of visibility enhances coordination and helps companies find opportunities for the best use of resources and apply solutions that generate value throughout the supply chain. This whole approach is critical in the complex practice of circularity and guarantees sustainable development as a data-oriented transition from a linear to a circular economy in practical operations (Yuan & Pan, 2023).

Big data analytics in the supply chain helps improve decision-making, increases visibility, enhances responsiveness, boosts agility, and allows more flexibility in satisfying demand. This is particularly important in a circular economy where many interdependencies between stakeholders must be smoothly managed regarding information and resources. Different studies reveal how big data is used in transportation sector industrial operations, inspiring sustainable practices and finally underlining the need for inter-organizational data sharing to reach a circular economy (Estarrona et al., 2021). That can also be applied in manufacturing and production enterprises.

In addition to monitoring decision-making, extensive data analytics can trigger the creation of business models and innovative solutions that incorporate the principles of the circular economy. Big data analytics help organizations discover new and economically viable strategies that foster circularity by providing visibility on material flows and revealing optimization possibilities (Lee & Mangalaraj, 2022). Advanced analytics will further ease the execution of circular economy initiatives by enabling cross-organizational collaboration while allowing stakeholders to stay aligned on sustainability goals in a common data platform.

Use data-driven insights to enable strategic decisions around resource utilization optimization, waste minimization, and collaborative innovation with organizations. Sustainable, resilient operations based on integrating big data analytics and aligning digital supply chain capabilities with circular economy principles address significant environmental, social, and economic challenges while generating long-term value for all stakeholders. (Dwivedi & Paul, 2022; Hu et al., 2019).

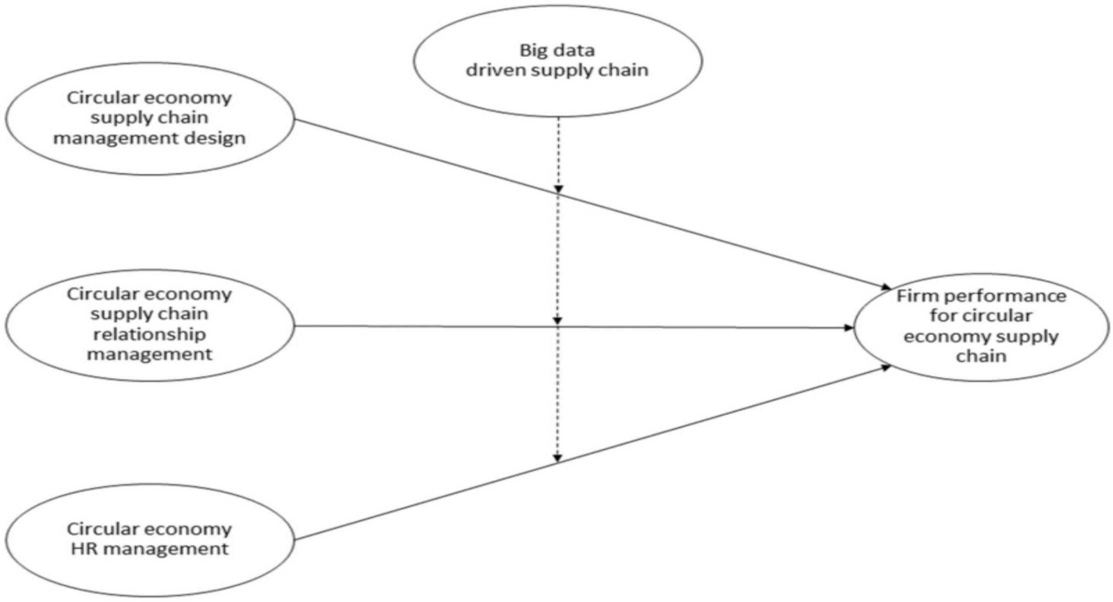

Figure 4. Conceptual model (Del Giudice et al., 2020)

The conceptual model in Figure 4 illustrates the relationship between circular economy supply chain practices and firm performance, with big data as a moderating factor. The model identifies three key components of circular economy supply chain management: supply chain management design, supply chain relationship management, and human resource management (HRM). The dotted arrow from big data analytics to firm performance indicates that its impact is a moderating rather than a direct influence. This means that while circular economy practices contribute to firm performance independently, their effectiveness is enhanced when big data analytics is integrated into supply chain operations. However, big data analytics plays a particularly strong role in moderating the impact of circular economy HR management, suggesting data-driven HR strategies. Overall, this model highlights the interconnected nature of digital transformation and circular economy principles.(Del Giudice et al., 2020).

Digital Twin technology is emerging as an innovative tool that can help align digital supply chains with circular economy goals; it is a digital counterpart to physical systems or system components. Digital twins facilitate the simulation and optimization of circular processes, thus enabling businesses and manufacturing companies to test and refine sustainable practices in a virtual environment before their physical-world implementation (Thelen et al., 2022; Klar et al., 2023).

A digital twin is a virtual simulation of a product, service, or process used to improve supply chain dependability, efficiency, and productivity. Strong in the link between the physical and digital worlds, it is related to sensors and a database that continuously gathers data. The optimization of resource use and minimization of waste fosters the principles of a circular economy, thereby fostering sustainability. Digital twins, by analyzing logistic data and IoT data, help organizations optimize energy use, trace materials, and recycle or remanufacture more efficiently. A flexible infrastructure is needed for handling large amounts of supply chain data for a closed-loop system that is both sustainable and efficient. (Khan et al., 2022).

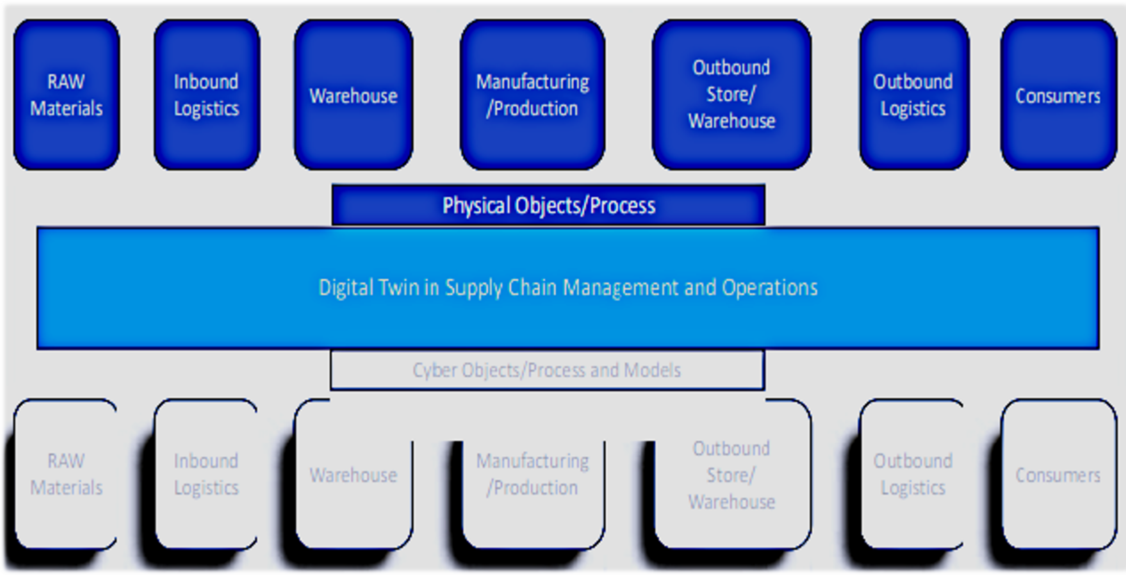

Figure 5. Digital twin in smart SCM (Khan et al., 2022)

Figure 5 illustrates the integration of Digital Twin Technology into Supply Chain Management (SCM) and Operations, highlighting the interaction between physical and digital processes. It presents a structured model where supply chain components, such as raw materials, inbound logistics, warehousing, manufacturing, distribution, outbound logistics, and consumers, are represented in two layers—physical objects/processes and cyber objects/processes and models. Digital Twin Technology allows organizations to optimize processes, detect inefficiencies, and improve sustainability performance by mirroring the entire supply chain in a virtual environment. It enables simulation-based planning, predictive maintenance, and scenario analysis, reducing risks and operational costs.

Over the last few decades, the evolution of technology has transformed how businesses work, and supply chain management (SCM) is no different. Some of these innovations, e.g., digital twins, have been reported to be of utmost attention (Liu et al., 2021; Marmolejo-Saucedo, 2020; Zhang et al., 2021; Wang et al., 2020). Digital twins – digital representations of physical assets, processes, or systems allow for deep synchronization and dynamic interactions between physical and virtual worlds (Wang et al., 2020). Not only does this enable planning, management, and optimization of supply chains, but it also allows organizations to move toward a circular economy. Digital twins enable businesses to pinpoint bottlenecks and optimize resource allocation and eco-friendly designs to pave the way for innovation and resilience in supply chain management.

By bridging the physical and virtual systems, digital twins provide an active medium in the digital supply chain that enables businesses and sectors to reach circular economy objectives. Using digital twin technology to handle supply chains has many advantages for management. (Wang et al., 2020) This technology helps operators to grasp their systems more precisely. By building comprehensive virtual models of supply chains or manufacturing systems, organizations could have real-time insight into material, energy, and information flow with digital twins. With less need for physical testing or experimentation, this all-encompassing perspective helps to find waste sources, pinpoint areas for value recovery, and expose inefficiencies. To ensure their feasibility and efficacy, it models in a virtual environment the environmental, financial, and operational effects of such policies (Romero et al., 2018). Digital twins also enable predictive analytics and decision-making power, enabling businesses to maximize resource use, extend product life spans, and reduce waste generation. Integrating digital twin technology in supply chains lets companies optimize operations, collaboration, and innovation of new sustainable practices. It makes it possible to run experiments on the digital twin first, where changes need to be effected, in order not to cause unplanned downtime or real-world model disruption. That is why a higher level of safety, labor protection, environmental safety, and economic efficiency can be achieved while designing and operating industrial production using an entire technological regime and environmental factor controls using the digital twin. (Rozhok et al., 2021). Thus, digital twins are one of the critical enablers of circular economy principles; they support industries in the transition from linear to closed-loop supply chain models, driving sustainability and long-term value creation (Klar et al., 2023).

Moreover, the concept of digital twin technology can help address the complexity that generally characterizes modern supply chains involving multiple stakeholders, diverse product lifecycles, and dynamic market conditions. Integrating data from different sources, such as sensors, enterprise systems, and external data feeds, offers a holistic view of the supply chain that helps spot opportunities to increase efficiency, cut waste, and improve sustainability (Kamble et al., 2021).

Digital twins are integral to the digital supply chain because they enable businesses and manufacturing organizations to drive toward circular economy goals. It has digital solutions, allowing companies to create virtual twins of physical systems. Companies can then use this digital twin to optimize processes, check sustainability strategies, or deploy processes more efficiently. In the context of the manufacturing use case, digital twins to monitor the supply chain and production processes, re-evaluate remanufacturing and reuse opportunities of a qualitative product or component, and integrate circular economy concepts throughout the product life cycle increase the demand forecasting, aggregate planning, and inventory planning levels thereby ensuring synchronization and optimization of supply chain activities. The provision of digital twin technology in the management of the supply chain is also a powerful opportunity for firms and manufacturing companies to increase operational efficiency, better decision-making, and better outmaneuver their competitors with deeper insight at the intersection of the physical and virtual worlds, dynamic and interacting (Rojek et al.2020; Liu et al.2021). These virtual simulations allow manufacturers to plot out how to minimize waste, extend a product's lifespan, and recover its value, all without the cost of physical prototypes or trial-and-error models.

Digital twins are also used in the logistics industry to replicate the flow of goods and materials across networks. They help to maximize reverse logistics, spot modal shift opportunities, and replicate the application of circular economy ideas in complex supply chains. (Ali et al., 2023). This allows businesses to evaluate and adopt efficient, sustainable logistics practices that support circular economy goals. So, they position themselves as strong vehicles across digital supply chains to empower enterprises with actionable insights and predictive capabilities. They enable them to make informed decisions that reduce waste and foster sustainable practices that drive their circular economy ambitions.

According to (Khan et al., 2022), from the manufacturing and distribution centers' perspective, Digital twins can help create 3D models of warehouses or distribution centers and all static or dynamic objects inside the facilities. Such a feature may be helpful, for example, in planning positions of inventories, defining quantities of products to be stored, and determining optimum routes for forklifts. Digital twins could significantly help build facilities according to products and operational requirements. Comprehensive data united within a digital twin can be key to optimizing employees' work. The Digital Twinning framework platform aims to address the significant challenges of the manufacturing industry supply chain distribution center, which can be summarized in Figure 6.

Figure 6 Digital twin in the supply chain (Khan et al., 2022)

The figure shows a digital twin (DT)-driven ice cream supply chain, integrating IoT and analytics to optimize sustainability and efficiency. From ingredient procurement to customer delivery, the DT monitors real-time data (e.g., storage conditions and machinery health) and simulates processes like warehouse capacity planning, production quality control, and cold-chain logistics. Predictive analytics preempt issues (e.g., equipment failures, spoilage), while route optimization minimizes delays and energy use. The DT enhances decision-making via KPIs (on-time delivery, cost efficiency) and reduces waste through dynamic adjustments, transforming traditional workflows into agile, eco-friendly systems.

The benefits of a digital twin-driven supply chain are massive. The digital twin will capture insights, operational and financial information, system configurations, device statuses, order statuses, and production orders, enabling the firm to anticipate upcoming operations and potential disruptions (Marmolejo-Saucedo, 2020). This will thus allow supply chain managers to make better decisions through process and workflow optimization, hence improving the resilience level of the overall supply chain. The supply chain will then be better prepared to withstand and recover from any unforeseen challenges or disruptions (Wang et al., 2020; Marmolejo-Saucedo, 2020; Zhang et al., 2021).

In data collection, digital twins with advanced technologies like IoT and artificial intelligence are included, which are critical in digital supply chains to support circular economy projects. These are essential to maximizing circular processes; these technologies enable real-time data collecting, predictive maintenance, and autonomous decision-making. The function of digital twins in facilitating the global shift to a circular economy will only become more important as that change accelerates. Working hand-in-hand, they allow businesses to create digital supply chains aligned with sustainability objectives, fostering innovation and more robust, sustainable economic models. Organizations can combine digital twins and advanced technologies to develop integrated data-driven solutions to execute circular economy initiatives. As an example, the collaborative integration of digital twins, enabled by AI-powered analytics, offers further insights into material flows, helping to identify chances for waste reduction and resource recovery, leading to the formation of dynamic, self-optimizing supply chain systems capable of adjusting to changing market conditions and sustainability targets (Chauhan et al., 2022; Khan et al., 2022).

Additive Manufacturing is a transformative technology process by which three-dimensional objects are created by the successive addition of material based on digital models. It has seen a fantastic increase in interest and uptake in the past few years. The technology is hailed for its potential to improve resource efficiency and sustainability as one part of the digital supply chain linked to the circular economy. (Despeisse & Ford, 2015) (Rejeski et al., 2017)

In addition, applying additive manufacturing in the supply chain can minimize inventory levels and optimize spare parts management. They can also be printed when needed, reducing the necessity of maintaining a vast inventory of spare parts. More than one supplier comes to a supply chain, which reduces cost and, hence, supports the supply chain efficiency. Additive manufacturing has advantages over traditional forms of production, such as the ability to create complex geometries, shortened lead times, and product customization (Rejeski et al., 2017). These characteristics could be essential for the flow of supply chains and the company's structure. One of additive manufacturing's main advantages is simplifying and shortening supply chains. By enabling local and demand-based manufacturing and more flexible and responsive supply chains, additive manufacturing helps to lessen the need for long-distance shipping and centralized factories. (Corsini et al. 2020).

Additive manufacturing shortens supply chains but also changes the nature of interactions between different players in the supply chain. This has been particularly the case in the humanitarian sector, where additive manufacturing has been instrumental in developing new supply chain models, highlighting challenges and complexities associated with introducing this technology into existing structures (Corsini et al., 2020). It has the potential to disrupt traditional distribution systems and open new opportunities for collaboration and innovation.

A simulation study by Rinaldi et al. (2021) highlights that additive manufacturing can affect the supply chain's performance, depending on the system setup and integration of additive and traditional technologies. These results show that adopting additive manufacturing in supply chains depends upon the production capacity and lead times involved, as well as how the different manufacturing methods are integrated.

Additive in nature, the manufacturing process is naturally less wasteful than conventional subtractive manufacturing techniques. Along with saving material inputs, this helps the environment by lessening the effects of disposal and extraction. By allowing on-demand production of customizable goods, additive manufacturing also helps with resource efficiency by reducing the risks of oversupply and product obsolescence (Despeisse & Ford, 2015). In additive manufacturing, one of the advantages is that it utilizes the best materials. According to Liu et al. (2023) and Agrawal et al. (2023), it ensures that raw resources are only used where needed, saving zero waste during manufacture and up to 90% as it forms things layer by layer. Machining and other conventional subtractive operations produce a lot of scrap material that can be challenging to recycle or use. Design-wise, AM removes this waste.

The other significant advantage of AM is that it supports the efficient extension of product life through effective repair and maintenance. The ability of AM to produce tailored replacement parts decreases the need for complete product replacement. This becomes very important in the aerospace and automotive industries, where the availability of replacement components at the right time can result in a big difference in resource efficiency (Hettiarachchi et al., 2022; Liu et al., 2023). AM could also be integrated with digital supply chains to enable on-demand production, reducing dependency on traditional inventory systems. Digital technologies allow supply chains to respond dynamically to the need for maintenance by ensuring that replacement parts are produced and delivered precisely at a time of need. This symbiosis supports remanufacturing and refurbishing practices according to CE principles to keep products and materials in use for as long as possible.

The same goes for additive manufacturing in the digital supply chain. It can create more flexibility by providing responsive digital designs to a supply chain when employed as an additive manufacturing strategy. It can reduce the environmental costs that traditional supply chain activities incur (Despeisse & Ford, 2015). The potential of additive manufacturing is, in any way, the ability to rapidly prototype, test, and manufacture parts with high-end material properties and functionality.

Since AM is distributed, localized production is possible, lessening the environmental impact of logistics and transportation. AM removes the inefficiencies of overproduction and too high inventory storage by allowing on-demand manufacture (Dwivedi & Paul, 2022; Marmolejo-Saucedo & Hartmann, 2020). Reducing greenhouse gas emissions and energy consumption across supply chains depends mainly on this capacity. Customizing is another benefit of localized production since it lets manufacturers create parts that fit particular consumer needs instead of mass production.

The concept of "**Cloud Computing**" has one of the most significant meanings in supply chain management in the era of computers. Embedding cloud computing into the digital supply chain has many advantages when businesses want to continue maintaining the circular economy. Cloud computing allows everyone in the supply chain to collaborate efficiently. Hence, it becomes easier to have information flow and activities coordinated well. (Andronie & Ionescu, 2021).

According to (Sundarakani et al., 2019), Cloud computing increases the efficiency of a supply chain because it enables real-time data exchange, automation, and scalability between suppliers, manufacturers, and distributors. For example, the hybrid SaaS model combines public and private cloud environments to ease licensing, security, workflow automation, and data backup. This improves collaboration, resilience, and cybersecurity in supply chains. Further, cloud computing supports the circular economy through resource-use optimization, reduction in waste, and enabling reverse logistics. They allow tracking products in the cloud, facilitating recycling, and improving lifecycle assessment to drive sustainability. Create a more agile, transparent, and circular supply chain ecosystem with cloud analytics and automation in the organization.

Figure 7 below illustrates the role of a cloud computing environment in connecting key elements of the supply chain—suppliers, manufacturers, warehouses/distributors, retailers, and customers. Through centralized cloud integration, information is seamlessly shared across all parties, enhancing collaboration, real-time visibility, and decision-making within the supply chain network.

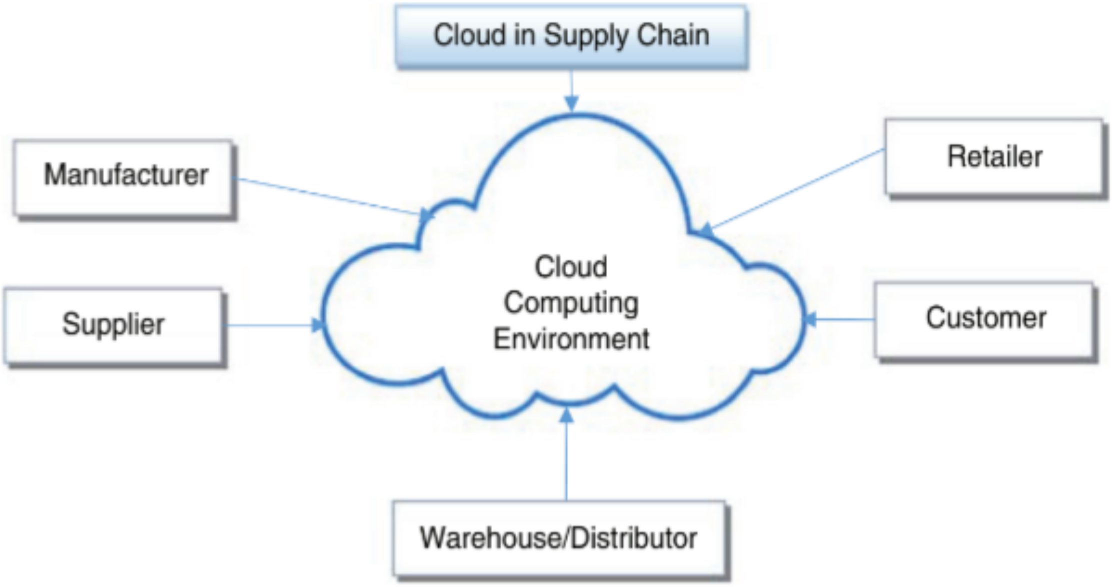

Figure 7 Cloud in supply chain network environment (Sundarakani et al., 2019)

Cloud computing has changed digital supply chains by offering flexibility and on-demand access to resources, including storage, computing power, and resources, while making it easier for stakeholders to collaborate and share data. This technology enhances openness and information sharing, leading to better decisions and the use of resources throughout the supply chain. This is important in achieving goals within the circular economy. Cloud computing has revolutionized how businesses handle and share data, connecting all stakeholders in real time. Thus, decisions can be very well-informed, quick, and practical to support the larger goals of Industry 4.0 and sustainable supply chain practices (Dwivedi & Paul, 2022; Hettiarachchi et al., 2022; Liu et al., 202).

Cloud computing is increasingly important in a circular economy since applying sustainability practices through strong messaging and data-sharing over the whole supply chain is necessary. Given the fast-evolving digital environment, one of the most important strategies any company can use to maintain a circular economy is to include cloud computing in the supply chain. For an organization to realize the environmental, social, and economic benefits of a circular economy, it has to manage and share data efficiently and also be able to collaborate effectively with its partners. (Giudice et al., 2020). The most crucial thing cloud computing has done is allow everyone within the supply chain network to share data in real time. In doing so, this feature erases information silos and thus ensures that parties involved, including manufacturers and retailers, have the correct and appropriate information at their fingertips (Dwivedi & Paul, 2022). For instance, cloud platforms make traceability of the different life cycle stages of a product, like design, production, distribution, and possible recycling, which aligns very well with CE principles (Marmolejo-Saucedo & Hartmann, 2020).

Moreover, cloud computing offers centralized and safe data storage and management, supporting data-informed decision-making in the digital supply network. Cloud computing lets companies readily access and examine real-time data. Imagine having access to all that data; it helps one react to supply chain or market changes and make wise decisions. Such adaptability is needed by managers and investors, and data security and cloud computing could meet both needs. (Liu et al., 2023). This repository facilitates the cooperation of many groups toward sustainability goals, the best use of resources, and the reduction of waste (Hettiarachchi et al., 2022).

Furthermore, by providing a centralized platform for data storage and management, the infrastructure of cloud-based services is significantly improving digital supply chains. In a circular economy, it is essential infrastructure for adequately tracking and controlling resource flows. Using real-time data access made possible by integrating cloud computing in digital supply chains, informed decision-making can be facilitated, lowering waste and optimizing resource allocation. Such openness, cooperation, and agility in data sharing along the supply chain in real-time guarantee that resources are used more effectively, and circular economy concepts are aligned (Giudice et al., 2020).

Transparency is indispensable for successfully implementing the circular economy in digital supply chains. This can be achieved through cloud computing, which ensures supply chain traceability. It allows for keeping a clear and accessible record of the flow of resources, origin of materials, and production processes, thus making it easier for all stakeholders to trace and authenticate each step of the supply chain. Such transparency helps to support better and more intelligent choices. It ensures that businesses follow sustainable methods, strengthening responsibility. Furthermore, it increases consumer confidence in the knowledge that a company is dedicated to moral and environmentally friendly operations, which becomes more crucial in the market today. (Agrawal et al., 2023).

Cloud computing systems use advanced data analysis tools to handle large amounts of information. This helps supply chain managers spot trends, fix problems, and find ways to use resources better. They can reduce waste and improve sustainability by predicting demand changes and matching production to what is needed, which helps avoid making too much. Cloud computing helps promote recycling and remanufacturing by providing helpful information about materials and products used. It highlights which parts can be reused or recycled, keeping materials in use for as long as possible. As digital supply chains become more complex worldwide, cloud computing and big data management have become very important. This helps organizations perform better financially and supports a sustainable future economy. (Dwivedi & Paul, 2022; Hettiarachchi et al., 2022; Khan et al., 2002).

2.6 Digital SCM & Circular Economy Framework

There is growing awareness that integrating Supply Chain Management (SCM) with Circular Economy (CE) principles plays an essential role in offering sustainability to modern supply chains. Thus, adopting digital technologies under Industry 4.0 and more recent paradigms such as Industry 5.0 plays a key role in enabling this shift by simplifying it to ensure transparency, efficiency, and adaptability. These are essential institutions related to sustainability, encompassing environmental, economic, and social dimensions.

The CE model from linear "take-make-dispose" to a circular system meant to lower waste and generate value in both waste and resource use, the CE model fundamentally changes. Digital SCM uses CE concepts to implement closed-loop systems whereby materials and goods are kept through constant reuse, repair, or recycling. It supports corporate practices, lowering environmental impact and improving economic well-being, as well as a regenerative resource management model (Sonar et al., 2022). By better monitoring, data analysis, and resource optimization, the digital SCM uses contemporary technologies for higher sustainability. Technologies, including the Internet of Things (IoT), big data analytics, and digital twins, that let businesses constantly monitor their supply chains and minimize inefficiencies that might lead to resource waste, support real-time tracking. By allowing data-driven decision-making processes that lower waste, energy consumption, and expenses and supporting CE principles, these technologies help to underlie sustainable practices. (Kazancoglu et al., 2023) .

Sustainable supply chain management's circular economy (CE) ideas center on the design of the product and process, circular inputs, and reverse logistics—that is, material collecting and reuse at the end of their life cycle. Supporting CE goals depends on collecting, managing, and directing materials for reuse or recycling; digital tracking allows this process using reverse logistics and traceability. Moreover, CE encourages the acceptance of the "10R" ideas (reduce, reuse, recycle, recover, repair, refurbish and remanufacture, refuse, rethink, and repurpose) to enable ideal resource use with minimal impact on the environment (Santiago et al., 2023).

Digital technologies that can help SCM integration with CE provide two pathways to sustainable supply chains through the demand and supply sides. This method also supports the environmental goals of an increasingly recognized industry 5.0 objective: establishing human-centered, environmentally sustainable systems that are also economically feasible. Thus, the proposition of sustainability dominance logic, when seen in conjunction with digital SSCM and CE, can help organizations meet key sustainable development challenges while adding necessary resilience to supply chains and delivery networks (Yadav et al., 2020).

One can achieve resource efficiency and lifeway sustainability by integrating sustainable digital supply chain management (SCM) with circular economy (CE) strategies. This integration uses digital technologies (DTs), including artificial intelligence, blockchain, and the Internet of Things (IoT), which leverage their transforming power. According to (Rusch et al., 2023), these DTs play a crucial role as enablers in reshaping supply chain operations to align with circularity principles. They achieve this by supporting real-time monitoring, increasing openness, and streamlining decision-making processes.

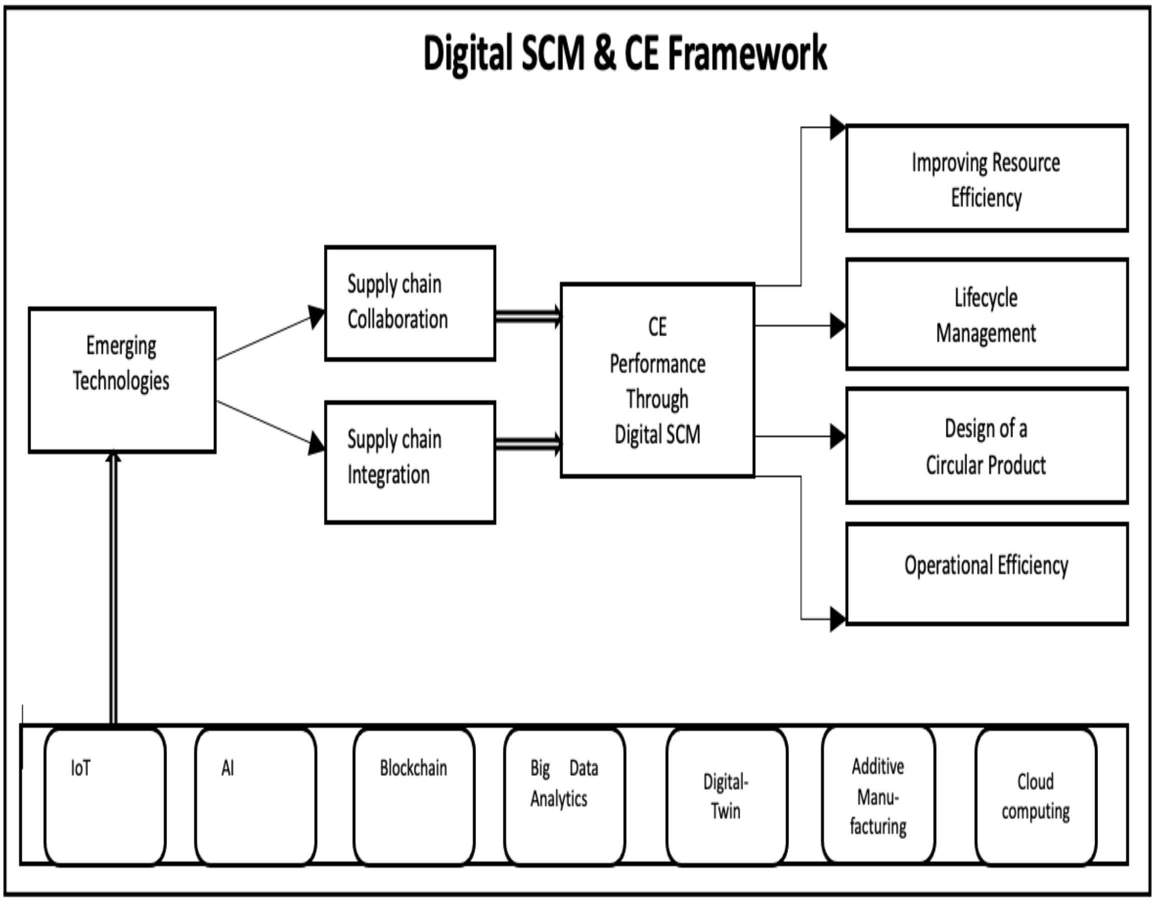

Figure 8 Digital SCM & CE framework (Author's work)

Figure 8 illustrates the Digital SCM & Circular Economy (CE) Framework, which shows how emerging digital technologies—such as IoT, AI, blockchain, big data analytics, digital twins, additive manufacturing, and cloud computing—support supply chain collaboration and integration. These efforts lead to improved CE performance through digital supply chain management. The framework emphasizes four key outcomes: circular product design, lifecycle management, operational efficiency, and resource efficiency, aligning digital transformation with circular economy goals.

The Digital SCM & CE Framework is developed based on many theoretical data and resource papers. It showcases how various emerging technologies, namely IoT, AI, Blockchain, Big Data, Digital Twins, Additive Manufacturing, and Cloud computing, improve collaboration and virtualization in SCM. Real-time monitoring, data-driven decisions, predictive analytics, and open operations enabled by these technologies help connect and streamline a supply chain using data.

Optimized resource management and seamless operations are ensured by supply chain integration, while stakeholders' coordination is enhanced through supply chain collaboration. A circular perspective for tracking the lifecycle of materials, sustainable operations, and optimized material flow is all established by digital SCM, which connects CE capabilities with digital transformation. As a result, organizations achieve critical circular economy objectives, such as improved operational efficiency, lifecycle management, circular product design, and resource efficiency. In conclusion, Digital Supply Chain Management (SCM) catalyzes sustainability, guaranteeing that the supply chain is more environmentally responsible, resilient, and intelligent, thereby achieving the objectives of the circular economy.

This shift to a CE is accompanied by a structural design change of the product to be more modulated, repairable, and recyclable, principles that reduce waste and optimize resource use (Ellen MacArthur Foundation, 2019). However, the practical application of these ideas depends on integrating digital supply chain technologies, which offer the required tools, infrastructure, and data-driven insights to match product development with circular economy objectives.

While **Designing of a circular product**, digital supply chain solutions become particularly beneficial since they enable better-informed decisions due to the availability of better data that can be used in product development. They also help the smooth sharing of data in real-time from all levels of the supply chain, becoming especially useful. Another example would be using generative AI that lets designers worldwide create new product designs targeted at sustainability by experimenting with alternative shapes, materials, and structures that boost product usage, thereby minimizing environmental consequences (Akhtar et al., 2024). These AI-driven simulations ensure product functionality while optimizing material use, reducing waste, and supporting circularity.

Besides this, big data-driven predictive analytics is essential for ensuring that materials used in product design are recyclable, sustainable, and durable. Digital supply chains can use product life cycle data, historical material performance data, and sustainability plans to proactively direct material selection toward long-term sustainability goals (Bocken et al., 2016). This loop optimizes circular product design repeatedly, ensuring that each product cycle advances circular economy principles.

Design for Disassembly (DfD), a foundational component of circular product design in digital supply chains, ensures that end-of-life (EOL) products can be easily disassembled, promoting material recovery and minimizing its environmental effects (Chauhan et al., 2022). Simulation tools/digital twins generate virtual prototypes for disassembly, thereby assisting manufacturers in designing products with optimal disassembly capabilities and reintegration into the supply channel (Tao et al., 2019).

Additionally, using IoT-enabled sensors also improves the effectiveness of DfD in digital supply chains because they enable constant monitoring of in-use data, wear behavior, and lifecycle performance. Such real-time insights allow for predictive maintenance, thus extending product lifespan and ensuring that components can be refurbished, repurposed, or recycled relatively easily (Ghobakhloo, 2020). Big data analytics further enhances reverse logistics optimization by simplifying the collection, refurbishment, and redistribution of products and materials, a critical element of circular supply chains (Rajput & Singh, 2019).

The role of collaborative digital platforms then adds another layer of relevance to the need for circular product design within the capabilities of digital supply chains (Zekhnini et al., 2021) since it enables real-time cooperation and collaboration to execute on all levels with designers, manufacturers, suppliers, and consumers. These platforms would allow stakeholders to share lifecycle assessment (LCA) data, optimize material choices, and co-develop sustainable products in line with market needs and regulatory requirements.

Furthermore, AI-powered supply chain platforms enable cross-functional decision-making to ensure that circular design principles are integrated into every product lifecycle stage. Integrating cloud-based digital ecosystems has the potential to speed up circular product innovation, improve supply chain agility, and enable a seamless transition to sustainable production models for the organization (Chen et al., 2023). One of the main challenges of circular supply chains is ethically sourcing components and materials for a circular product design, using them effectively, and returning them responsibly. Blockchain technology solves this problem by improving traceability and accountability and providing visibility of materials throughout their lifecycle, from sourcing to end-of-life recoveries (Saberi et al., 2019).

Using decentralized ledgers, blockchain allows safe tracking of parts and materials on its own so that all regulations of the circular economy can be met. Smart contracts and digital product passports enhance supply chain transparency, empowering manufacturers, suppliers, and consumers with up-to-date information on material origins, recyclability, and sustainability performance (Zhao et al., 2022). This real-time verification process assists businesses in making data-driven decisions that can lead to optimized material usage, ethical sourcing, and streamlined reverse logistics operations.

A key aspect of this is industrial **lifecycle management**, which allows products to be made, used, and disposed of sustainably throughout modern supply chains. Digital supply chain tools, such as digital twins, change the game with the virtual replica of physical assets. These tools simplify life cycle thinking, allowing organizations to evaluate impacts through scenario modeling and offering insights into product design and resource use improvements (Kurniawan et al., 2022). Digital twins, for example, enable companies to simulate a product's entire life cycle, from the extraction phase to end-of-life disposal, leading to finding opportunities to reduce waste material and increase the recyclability of the products (Tao et al., 2019). Blockchain enhances these efforts through its traceability potential, which allows for recording every stage of a product’s lifecycle, focusing specifically on environmental compliance and transparency (Caldarelli, 2024).

These decentralized and immutable ledger technology guarantees products comply with sustainability standards, ethical sourcing laws, and end-of-life recycling mandates. By combining blockchain with radio-frequency identification (RFID) and Internet of Things (IoT) sensors, companies can generate automated compliance reports, improve material traceability, and enhance accountability for extended producer responsibility (EPR) schemes (Saberi et al., 2019).

Employing IoT-enabled predictive maintenance, which lets companies extend product lifetime, is another vital component of lifecycle management in digital supply chains. IoT sensors send real-time data to manufacturers for proactive maintenance scheduling (Governindan et al., 2024), continuously monitoring product performance, wear patterns, and environmental conditions. This method maximizes replacement cycles and lowers the need for regular raw material extraction by preventing early product failure. Furthermore, greatly enhancing product dependability and sustainability, predictive maintenance driven by machine learning finds possible performance problems before they arise.

Big data analytics and artificial intelligence (AI) provide deep insights into consumer behavior patterns, material efficiency, and product performance, consequently improving lifecycle management. These digital technologies analyze vast amounts of lifecycle data to help businesses redefine product designs for durability, reparability, and recyclability (Lopes de Sousa Jabbour et al., 2020). Artificial intelligence-based product lifecycle analysis can identify inefficiencies in production, consumption, and end-of-life to enable firms to redesign material content, enhance end-of-life practice, and enhance remanufacturing (Bocken et al., 2016). Furthermore, AI-powered predictive analytics enhances reverse logistics and closed-loop supply chain operations. AI systems can optimize refurbishment processes by analyzing product return history and material recovery levels (Rajput & Singh, 2019). These features reduce the environmental impact and increase supply chain resilience by preventing the utilization of virgin resources.

Through the harmonization of collaborative cloud-based platforms, life cycle management processes remain interconnected among all supply chain members. Cooperative platforms allow for real-time data sharing among complex players such as designers, manufacturers, suppliers, retailers, and customers in parallel and allow effortless information sharing and harmonization of sustainability initiatives (Zekhnini et al., 2021). To ensure that products are made to be reused, remanufactured, and recycled from the start, companies can align their lifecycle strategies with the principles of the circular economy through cloud-based collaboration.

Cloud computing further improves material flow efficiency, enabling companies to monitor product lifecycles in real time, manage stock automatically, and improve reverse logistics processes. With these online platforms, companies can quickly meet environmental regulations and implement global guidelines for sustainability reporting and circular economy models (Geissdoerfer et al., 2017).

Improving resource efficiency is a key principle of the circular economy—where waste is lowered, environmental impact is minimized, and materials are used to their best—is resource efficiency, where waste is minimized. Through real-time monitoring, predictive analytics, and innovative automation solutions that simplify material flows and production processes, digital supply chains are essential for increasing resource efficiency. Big data analytics, blockchain, IoT-enabled sensors, and AI-based decision-making help companies improve operational efficiency, cut resource waste, and support circular economy ideas (Ching et al., 2022).

The Internet of Things (IoT) transforms resource management by using real-time material movement, manufacturing efficiency, and energy use. IoT-empowered sensors on supply chains and manufacturing equipment offer continuous data on resource consumption, which helps businesses find inefficiencies and maximize material use (Friedman & Ormiston, 2022). IoT-empowered intelligent manufacturing systems, for example, change production levels depending on real-time demand fluctuations, thus minimizing surplus resource use and energy consumption (Ghadimi et al., 2020).

Moreover, predictive maintenance enabled through IoT optimizes operational efficiency and reduces material waste as it anticipates large-scale equipment failures and helps avoid unplanned downtimes (Tiwari et al., 2021). Leveraging IoT with digital twins can help companies simulate production processes and trial strategies for resource efficiency in virtual environments before execution in physical operations, optimizing material use (Tao et al., 2019).

Resource efficiency, improved demand forecasting, production planning, and improved inventory management are some of the fundamental sectors that require big data analytics. AI-driven predictive models enable businesses to adjust their production schedules dynamically based on historical consumption patterns and real-time supply chain data, thus avoiding overproduction and the consequent accumulation of excess inventories (Ching et al., 2022). Such data-driven optimization minimizes wastage to a large extent, as it facets the supply chain, ensuring efficiency in using materials and energy (Lopes de Sousa Jabbour et al., 2020).

Big data analytics also ease resource planning strategy by identifying inefficiencies in supply chain processes, such that manufacturers can change production planning and material procurement depending on current levels of supply and demand (Friedman & Ormiston, 2022). The AI-based systems also improve remanufacturing and recycling activities to reclaim, rework, and reuse materials within production cycles rather than disposing of them (Bocken et al., 2016).

Blockchain technology guarantees end-to-end traceability, transparency, and compliance with sustainability goals, strengthening resource efficiency in digital supply chains. Blockchain records' immutable and distributed character helps companies track raw materials, check their sustainability credentials, and guarantee responsible sourcing

(Caldarelli, 2024). Blockchain-enabled smart contracts let businesses track resources automatically, check supply chain sustainability, and improve material flow responsibility (Saberi et al., 2019). By ensuring that recycled and reclaimed materials are effectively reintegrated into manufacturing cycles, this traceability characteristic supports circular economy goals and helps material recovery efforts (Zhao et al., 2022). In addition, decentralized ledgers, with the aid of blockchain, enable various stakeholders to collaborate, and suppliers, manufacturers, and consumers can obtain proper information regarding the origin of the material, prior utilization, and recycling routes. Real-time visibility of resources assists companies in simplifying material flow so that waste is reduced, and resource efficiency is enhanced (Geissdofer et al., 2017).

Stakeholders in supply chains must work together to maximize resource efficiency and reduce waste. Cloud-based collaboration systems enable manufacturers, suppliers, and logistics partners to schedule production, coordinate utilization of resources data, and match sustainability strategies (Zekhnini et al., 2021). Closed-loop material management systems enable businesses to use secondary raw materials in manufacturing and recycle excess materials and byproducts (Rajput & Singh, 2019). Digital collaboration tools allow seamless communication and data sharing, promoting circular resource flows and extending material use before being recovered and reused (Chen et al., 2023). This networked approach promotes resource efficiency across industries and supply chains, strengthening the circular economy model.

A modern supply chain should have **Operational efficiency** to be sustainable and competitive. For the circular economy (CE), it is easier with digital technologies to comprehend what's happening within the supply chain, decide, monitor it in real-time, and make the best use of the given resources. This means that operations are done efficiently to create the least possible amount of waste, emit the fewest pollutants, and be as productive as possible (Dolgui & Ivanov, 2022). When making firms efficient and according to the philosophy of the circular economy, they can employ IoT, blockchain, AI-driven analytics, and cloud computing.

The Internet of Things (IoT) plays a significant role in ensuring efficiency in supply chain operations by tracking goods, drivers, and warehouse inventory in real-time. The application of IoT-enabled RFID tags and GPS tracking technologies provides companies with timely feedback regarding their products' locations, which cuts down transit time, makes it easier to run supply chains, and allows the unrestricted movement of goods (Broccardo et al., 2022).

The Internet of Things (IoT) and blockchain technology offer real-time, accurate, secure, and transparent tracking data. Blockchain decentralized ledgers allow companies to know where products originate, monitor their inventory better, and monitor transport conditions, which enhances operational performance and minimizes the environmental footprint (Saberi et al., 2019). IoT and blockchain, hand in hand, strengthen the effectiveness of recycling and product recovery, thereby making reverse logistics more robust. This ensures that materials are recovered and recycled within the supply chain (Zhao et al., 2022).

Operational sustainability mostly depends on transportation efficiency, influencing emissions, fuel consumption, and delivery time. Using historical logistics data, weather forecasts, and traffic, machine learning algorithms and AI-based predictive analytics examine transportation routes to optimize them, thereby considerably decreasing fuel consumption, operational costs, and CO_2 emissions (Dolgui & Ivanov, 2022). Demand forecasting driven by artificial intelligence also helps avoid needless transportation so that supply meets demand without needless resource use. With AI-powered fleet management systems, Companies can lower idle vehicle use, lower emissions, and increase logistics efficiency, helping to support circular economy targets (Tiwari et al., 2021).

Through cloud computing and digital twins (real-time digital copies of storage facilities), companies can optimize the warehouse layout, automate inventory management, and accelerate order fulfillment (Tao et al. 2019). This kind of virtual modeling can help exercise operational efficiency for better resource allocation, reducing production and storage costs (Ghadimi et al., 2020). A key way to boost efficiency and eliminate waste is by enabling effective communication and collaboration between all aspects of the supply chain. Cloud-based digital platforms enable seamless data sharing by manufacturers, suppliers, distributors, and retailers to ensure quick decisions, shorter lead times, and better operational coordination (Ching et al., 2022). These platforms improve supplier transparency, production schedules, and distribution schedules, all of which help ensure supply chain activities align with sustainability goals. Real-time data-sharing integration allows organizations to respond rapidly to market changes, reduce waste and energy consumption, and enhance operational efficiency (Geissdoerfer et al., 2017).

3 Methodology

This chapter identifies the methodological framework to study how circular economy (CE) strategies are adopted through digital supply chain strategies, emphasizing the role of emerging technologies in promoting sustainability. The qualitative research design uses thematic content analysis of corporate sustainability and annual and financial reports. This perspective is employed to reflect the complexity of the digital supply chain transformation and to detect how it contributes to alignment with CE principles while providing rich contextual data on organizational practices, challenges, and innovations.

3.1 Research approach and design

In the context of this research, the study primarily applies qualitative content analysis, which, according to Krippendorff (2018), is an analytical method that examines textual data systematically and objectively to identify consistent topics and themes. This approach is rooted in the interpretivist and constructivist paradigms (Guba & Lincoln, 1989; Denzin & Lincoln, 2018). It shows that knowledge is co-constructed through subjective interpretations of organizational practices. This makes it a great way to look into how companies use digital technologies to help them reach their sustainability and circular economy (CE) goals. Qualitative content analysis is perfect for this study because it lets us look closely at corporate sustainability reports, which are full of stories about strategies, problems, and new ideas. Qualitative content analysis, on the other hand, focuses on the depth of the text, which fits with the study's goal to figure out the hidden and apparent themes in corporate disclosures (Mayring, 2014; Neuendorf, 2017).

This study draws on an inductive approach in its analysis, whereby themes emerge organically from the data rather than being imposed through preconceived ideas (Patton, 2015; Charmaz, 2006). Such flexibility is critical given the emerging theories and changing industry practices surrounding digital supply chains and circular economy (CE) frameworks (Seuring & Müller, 2008). Creswell and Poth (2018) stated that inductive methods enable researchers to adjust as new information arises — for example, how blockchain increases traceability or how AI also helps reduce waste — instead of being constrained by set models.

There are three main reasons why qualitative content analysis is crucial in this research. As such, it provides both a systematic and adaptable approach to analyzing complex text-based data, such as sustainability reports. There is no shortage of reports conflating technical aspects of digital tools (IoT, twins, etc.) and wide-sweeping statements about goals for sustainability (Bryman, 2016).

This approach allows researchers to explore deeper meanings and uncover hidden messages that might go unnoticed if they were examining numerical data alone (Kohlbacher, 2006). A quantitative study, for example, might count the number of times “blockchain” is mentioned. Still, qualitative content analysis can reveal how companies describe the role of blockchain in their circular economy efforts, such as improving the tracking of materials or incentivizing collaboration. Third, this method employs systematic coding to allow room for readers to judge the thoroughness and transparency of the research process, which is particularly relevant to the analysis of corporate reports (Elo & Kyngäs, 2008).

With a strict emphasis on qualitative content analysis, this study privileges depth rather than breadth, allowing for a thorough investigation into how multinational corporations (e.g., Danfoss, ABB, Schneider Electric) communicate their digital and CE strategies. This is consistent with Neuendorf’s (2017) explanation that content analysis closes the gap between qualitative richness and methodological rigor, making it particularly suited to eyes set on trends in developing fields such as sustainable supply chain management. In addition, it addresses the need for contextual specificity in sustainability research, as highlighted by Mayring (2014), by situating findings within each company's unique operational, regulatory, and cultural environments.

3.2 Justification for a qualitative approach

The study uses qualitative thematic content analysis, which is appropriate to analyze how enabling technologies of the digital supply chain (i.e., IoT, blockchain, AI, big data analytics, digital twin, additive manufacturing, and cloud computing) contribute to circular economy objectives. Qualitative methods are adaptable and flexible and thus well-suited for emerging and dynamic trends in business as industry practices, policies, and strategies evolve continuously (Silverman, 2020).

Furthermore, qualitative research is context-specific, providing a unique approach to investigating organizational structures, operational models, and sustainability commitments related to digital supply chains (Denzin & Lincoln, 2018). Implementing a circular economy is often a complex process associated with a change in the organization's culture, as well as the need for cooperation between multiple stakeholders and the integration of particular technologies. Therefore, qualitative research becomes the most suitable approach to exploring these elements (Saunders, Lewis, & Thornhill, 2019).

Since this study covers multiple fields, namely digital supply chains, circular economy, and emerging technologies, rather than testing fixed ideas, the study allows key themes to be generated from the data naturally (Stebbins, 2001; Patton, 2015). This research is guided by the interpretivist and constructivist perspectives, which consider the various perspectives of knowledge and how it is constructed through experiences (Bryman, 2016; Denzin & Lincoln, 2011). It assesses how multiple stakeholders—businesses, policymakers, and industry specialists—approach digitalization and sustainability in supply chain management.

3.3 Data Collection

This study implements a rigorous multi-source qualitative data collection methodology, primarily collected from corporate sustainability reports, annual reports, and financial reports, to investigate integrating digital technologies in the supply chain to achieve circular economy (CE) strategies. The dataset consists of sustainability reports from 18 companies; 10 represent multinational corporations (MNCs) across various sectors—industrial automation, logistics, energy, pulp and paper, and smart manufacturing. Out of them, 12 are local companies (of Finnish origin). These companies were selected following a purposive sampling strategy guided by three main criteria to provide methodological coherence and relevance to research objectives:

Firstly, Companies were selected based on their practical applications of digital supply chain technologies (IoT, blockchain, artificial intelligence (AI), and digital twins), as demonstrated in their public reports. This fits the study's emphasis on the ways technology fuels sustainability. Digital tools increase the transparency and efficiency of supply chains, which makes them necessary for this study (Seuring and Müller, 2008).

Second, the sample only covered companies with publicly available complete sustainability reports. These reports are based on standardized guidelines like the Global Reporting Initiative (GRI) and the European Union's Corporate Sustainability Reporting Directive (CSRD, 2023). Approaches based on these frameworks provide reliable data and enable organizations to make meaningful comparisons (Baumüller & Sopp, 2022).

Third, it required companies to participate in circular economy projects, such as closed-loop production cycles, material recovery initiatives, and waste minimization programs. This criterion encapsulates the aim of this study, which seeks to stimulate the conversation concerning the intersection between digitization in their supply chain and the principles of circular economy (Geissdoerfer et al., 2017).

This group of corporations is selected based on a cross-sectoral and geographically diverse sample, including leaders in industries driven by sustainable goals and circular objectives. For example, ABB and Schneider Electric were considered industrial automation companies making strides in AI-driven energy efficiency. Wärtsilä and Posti were analyzed as logistics giants investigating blockchain-enabled supply chain traceability. On the other hand, pulp and paper companies such as Stora Enso and Huhtamäki were selected for their expertise in biodegradable material flows and circular material flows. The sample includes companies from the Nordic, European, and global regions with branches in Finland. This shows how regulatory frameworks and sustainability practices vary from region to region, as Hąbek and Wolniak (2013) stated in their study of EU sustainability policies.

In this research, the data collection process included triangulation—a technique suggested by Flick (2018) to validate conclusions across several data sources—to increase methodological rigor. Even though other materials, including annual reports, whitepapers, and corporate ESG (i.e., Environmental, Social, and Governance) statements, were examined to provide further context to technological and CE commitments, sustainability reports represented the primary data source (Bowen, 2009). However, the multi-layered in-depth analysis method employed in this study minimizes the likelihood of superficial judgments to evaluate multiple logics presented in texts and, thus, enhances the study's internal validity by examining not only explicit assertions but also implicit strategic emphases in narratives (Bowen, 2009).

The study acknowledges that multinational corporations (MNCs) and regional companies significantly impact global supply chain practices and can test innovations everyone can use (Koberg & Longoni, 2019). However, small and medium-sized businesses (SMEs) are not included intentionally. This is because of the need for standardized, detailed data on digital-CE integration, which is something that SMEs often fail to meet because they don't have enough resources (Rizos et al., 2016).

Danfoss was established in Denmark in 1933, gradually expanding into one of the global leaders in industrial automation, climate solutions, and energy-efficiency technologies. The company has branches in over 100 countries, with a stronghold in Europe, North America, and Asia. Danfoss started its operations in Finland in 1971, strengthening its footprint in the Nordic region. Danfoss employs some 42,000 staff globally and achieved a turnover of about €10.3bn in 2023. Specializing in smart heating and cooling systems, digital fluid control, and industrial IoT applications. Its industrial solutions incorporate emerging technologies, such as AI, digital twins, and predictive maintenance, to improve efficiency and sustainability in its operations. Danfoss plans to be carbon neutral by 2030 with green energy solutions and circular economy practices. Danfoss is seen as a leader in smart factory technologies that use automation and real-time data analytics to make the manufacturing supply chain more efficient. They are also making progress in electrification and storage solutions for renewable energy to help with efforts to make the world more sustainable. With its digital innovations, Danfoss is changing supply chains through smart logistics and using artificial intelligence (AI) to allocate resources.

Nokia started as a paper mill. Nokia, which began in Finland back in 1865, grew to be a major player in digital infrastructure and telecommunications worldwide. The company has almost 86,000 employees and works in more than 130 countries. Nokia's revenue 2023 reached €24.9 billion because of its 5G, AI, and IoT solutions. Nokia is leading the way in digital supply chain innovations, utilizing blockchain for tracking products, AI to simplify networks, and cloud computing to keep data secure. It uses smart digital twin technology focused on sustainability to get the most out of infrastructure projects. Nokia has set a goal to become carbon neutral by 2040. They're putting much effort and money into creating energy-efficient networks and sustainable products. Nokia supports the circular economy with recycling and reuse programs, ensuring old network equipment gets a new life. They're also partnering with governments and businesses to help create smart cities and build the next wave of digital infrastructure. Using AI-driven predictive analytics, Nokia ensures everything runs smoothly and is eco-friendly throughout its supply chain.

Wärtsilä is an industry pioneer in maritime and energy solutions, emphasizing smart power systems and decarbonization. The company was founded in Finland in 1834. It has 17,500 employees and operates in over 70 countries, generating €5.8 billion in revenue in 2023. Wärtsilä is leading the way in innovation. They're working on AI-driven systems to optimize fuel use, creating digital models of ships, and using predictive maintenance to help cut down emissions in the maritime industry. They're also pushing for cleaner energy by encouraging hybrid power options and alternative fuels for shipping, aiming to hit net-zero carbon emissions by 2050. In order to make Wärtsiläs marine and energy products more energy efficient, Wärtsilä uses automation and real-time data analytics in its operations. In addition, it has improved the supply chain's visibility and performance by implementing contract management systems based on the blockchain. Two of Wärtsilä's circular economy initiatives are remanufacturing components and using recyclable materials. The company collaborates with logistics providers and ports to improve port efficiency with AI. Wärtsilä is revolutionizing energy production and distribution worldwide through its smart grid solutions and renewable energy storage.

Stora Enso is a Finnish-Swedish company formed in 1998 by the merger of two companies. However, the company originally started in the 16th century. Today, it operates in over 50 countries and has roughly 20,000 employees worldwide. In 2023, they were recognized as one of the best packaging companies, raking in €9.4 billion, thanks to their groundbreaking work in biodegradable packaging and sustainable forestry. The company is truly leading the way by utilizing blockchain and AI to streamline its supply chain, reduce waste, and promote sustainable practices. They have signed on to an ambitious pledge to be fossil-free by 2050 and are investing in carbon-neutral factories and initiatives aimed at a circular economy. Stora Enso uses its digital supply chain tools and predictive analytics to drive efficiency and support greener manufacturing decisions. They're also using AI to control quality in pulp and paper production systems and reduce waste. What's more, Stora Enso is taking the lead in 3D printing with bio-based materials, exploring new methods for bolstering sustainable construction. Working with industry leaders and government authorities, they're a leading force in the transition to a low-carbon economy and bio-based economy.

Capgemini was founded in France in 1967. Capgemini is a power player in consulting, IT, and digital transformation services. They now employ over 340,000 people in more than 50 countries. They said they made €22.5 billion in 2023. Their migration to Finland in 1998 propelled them to a more prominent status within the Nordic tech scene. Capgemini specializes in AI-driven analytics, cloud computing, and cybersecurity, enabling companies to extract maximum value from their digital supply chains. They use artificial intelligence to more accurately forecast what supplies they will require and blockchain technology to increase transparency in the supply chain. It also highlights how green-certified digital solutions can help businesses reduce their carbon footprint through advanced technology. The company has a strategy to implement parts of a circular economy, including green data centers and cloud services that use AI components to optimize for less energy consumption and emissions during operations. They will be going carbon-neutral by creating IT infrastructures without any carbon in the process, which makes the tech eco-friendlier. Capgemini helps large companies and government authorities make digital supply chains more secure. They also create digital twin models that simulate supply chain processes, making them more efficient and environmentally friendly.

Logisnext Finland is an industry leader in logistics and material handling solutions, specializing in smart fleet management and automated warehouse systems, and is part of Mitsubishi Logisnext. The company has over 13,000 employees worldwide, focusing on customers in North America, Europe, and Asia. Logisnext, which specializes in artificial-intelligence-powered automation, electric material handling vehicles, and internet of things-based fleet tracking systems, generated close to €4 billion in sales in 2023. The company uses digital logistics platforms and predictive maintenance analytics to increase efficiency and reduce emissions. Logisnext offers circular economy principles in equipment lifecycle management to promote sustainable warehousing. Hydrogen-powered forklifts have been unveiled, while the company is also collaborating with various players to build fully autonomous warehouse ecosystems. A powerful AI-driven logistics platform is also helping the company bring progressive evolution to managing material handling, all while being cost- and environmentally friendly solutions.

Posti was founded in 1638 in Finland. It is considered the principal postal and logistics company in the country. Currently, it operates in Finland as well as Sweden, Norway, and the Baltic region. The company has around 20,000 employees and achieved revenue of 1.6 billion euros in 2023. Posti has spent hundreds of millions of euros on AI-driven logistics optimization, computerized sorting houses, and renewable transport initiatives. It aims to utilize 100% fossil-free transport by 2030 and electrified delivery trucks and replacement fuels for its fleet. Real-time IoT tracking energy consumption to optimize delivery efficiency and sustainability. Posti's services use data-powered route planning to minimize emissions and improve the efficiency of last-mile delivery. Posti is constantly collaborating with e-commerce platforms and sustainability partners to develop closed-loop recycling solutions for packaging. With its digital logistics solutions, Posti is making daily business operations leaner while decreasing its environmental footprint significantly.

Schneider Electric was established in 1836 in France and is currently considered a global leader in energy management, industrial automation, and digitization. The organization has a presence in more than 100 countries with approximately 150,000 employees, with the reported turnover of the company being €35.9 billion in 2023. Schneider Electric came to Finland in 1975 and further solidified its position in the Nordic energy and technology industry. Schneider Electric integrates AI, IoT, and blockchain technologies to enhance energy efficiency and supply chain sustainability. The company has also adopted digital twin technology and predictive analytics to maximize the use of resources and sustainable manufacturing processes. Schneider Electric aims to achieve net-zero emissions by 2050 through renewable energy, circular economy practices, and intelligent manufacturing. Schneider Electric collaborates with industry leaders, governments, and technology companies to help drive global sustainability. Schneider Electric has pioneered closed-loop materials reuse and smart grid systems to improve industrial energy efficiency.

Kone was established in Finland in 1910. Kone is a world leader in elevators, escalators, and smart building solutions. It has branches in more than 60 countries and has approximately 60,000 employees, with sales of €11.0 billion in 2023. Kone uses emerging technology in its system, such as AI, IoT, and predictive maintenance technology, in its smart urban mobility solutions to make them energy-efficient and provide an excellent customer experience. It has invested in digital twin technology and cloud-based analytics to optimize building performance and minimize downtime. Kone plans to be carbon neutral by 2030 by utilizing green materials, circular business models, and smart energy solutions. It uses blockchain technology to provide supply chain transparency and recycle materials in its elevators and escalators, so there will be little wastage. Kone's sustainability strategy is to enhance energy efficiency in vertical transportation, reduce Scope 1, 2, and 3 emissions, and make it 100% renewable worldwide. As a digital leader, Kone creates smart, sustainable cities with reduced environmental impacts. Kone collaborates with urban planners, architects, and real estate developers to develop future-proof, sustainable mobility solutions. Kone also strongly believes in circular economy thinking, designing products to last the long term, and remanufacturing for reuse.

Valmet, which was founded in 1951 in Finland, is a global leader in process technologies for the paper, pulp, and energy industries. Valmet has operations in more than 30 countries with 17,000 employees and reported a revenue of €5.5 billion in 2023. Valmet has embraced IoT-based industrial automation, AI-based predictive analytics, and digital twins to promote resource efficiency and sustainability. The organization is committed to sustainable manufacturing through the encouragement of closed-loop systems, bio-based materials, and energy-efficient technology. Valmet is a leader in smart production monitoring to drive supply chain transparency. It works with circular economy stakeholders, like their businesses, to create more sustainable material processing processes. Its digital solutions minimize carbon emissions, maximize process efficiency, and enhance lifecycle management. The organization has also invested in waste-to-energy conversion to aid global sustainability initiatives.

Wipak, headquartered in Finland, is a top sustainable and recyclable packaging solutions provider. Wipak operates offices in various economies across Europe and has a workforce of 1,800 employees with a turnover of around €400 million in 2023. Wipak embraced AI-facilitated material optimization, closed-loop recycling, and biodegradable pack solutions to have minimal environmental contributions. With blockchain technology, Wipak is making its supply chain more traceable. To provide additional customer support, they are also adopting digital labeling. Wipak is building factories fueled by renewable energy and introducing more usage of bio-based materials to reach its target of being carbon neutral by 2025. To encourage circular packaging practices, they are working with businesses and governments. Also, they can reduce energy consumption in production because of intelligent machine learning.

Huhtamäki is a Finnish-origin company founded in 1920. They are well known for their sustainable packaging. With operations in over 37 countries and 18,000 employees worldwide, Huhtamäki reported €4.2 billion in revenue in 2023. Through circular economics, Huhtamäki aims to minimize its environmental footprint using bio-based packaging materials, recyclables, and innovations. It incorporated AI-driven material selection and blockchain-traceable supply chain technology. The firm is focused on eliminating single-use plastics and utilizing compostable and biodegradable packaging in its offerings. Huhtamäki collaborates with large retailers to create closed-loop recycling technologies that extend the packaging life cycle. Huhtamäki has invested in smart pack technology, such as IoT-based monitoring, to establish maximum logistics efficiency. The company plans to be carbon neutral by 2040, using renewable energy-driven production facilities. With automation and real-time data monitoring, Huhtamäki is also minimizing the use of resources in operations, making it more efficient.

Asea Brown Boveri, also known as **ABB**, was founded in 1988 through the collaboration of Sweden-based ASEA and Brown Boveri from Switzerland. It works in industrial automation, robotics, and energy-efficient solutions. ABB has operations in more than 100 countries, employs 105,000 people, and posted a turnover of €32 billion in 2023. ABB started its Finnish operations in 1991, further enhancing its foothold in the Nordic region. ABB combines AI-based robotics, IoT-based smart grids, and predictive maintenance technology to maximize efficiency and sustainability. Its decarbonization strategy emphasizes electrification, renewable energy solutions, and digital twin technology for industrial automation. ABB also developed blockchain carbon footprint tracking systems to help ensure compliance with sustainability. In addition, ABB promotes circular economy initiatives like remanufacturing electrical goods and zero-waste production processes. It has set a goal for carbon neutrality by 2030 and will transition all of its supply chains to renewable energy by 100%. The firm works with the automotive, logistics, and energy sectors to create smart and sustainable infrastructure solutions. ABB has also established AI-driven energy optimization solutions through which industries can minimize emissions and maximize efficiency. With its sustainable innovation focus, ABB is in charge of digitalizing industrial automation.

Vaisala was established in 1936 in Finland. Vaisala operates weather, environmental, and industrial measurement technology businesses. It operates in more than 150 countries and has about 2,000 employees, with revenues in 2023 of €552 million. Vaisala creates sophisticated climate observation solutions, Internet of Things-connected weather sensors, and artificial intelligence-based environmental analytics to benefit industries from aviation to renewable energy. It combines forecast weather analysis and current climate information into digital platforms for enhancing operational effectiveness and risk reduction. The company minimizes its carbon footprint by encouraging sustainable business practices, a circular economy, and intelligent energy solutions. Vaisala employs machine learning-based weather forecasting models to enhance weather forecasting and climate resilience. Their tech solutions help companies move towards climate-positive operations by improving energy efficiency and meeting sustainability standards. They also collaborate with global environmental groups and policymakers to push for data-driven actions in climate and sustainability reporting.

Metso was originally founded in 1999 in Finland. It deals with the mining, aggregates, and metals processing solutions sector. Metso has over 50 sites worldwide, employs approximately 16,000 people, and recorded revenue of €5.3 billion in 2023. Metso is well-known for its sustainable mineral processing, energy-efficient solutions, and AI-driven automation of industrial processes. The firm employs emerging technologies, such as digital twins, real-time analytics, and predictive maintenance technology, to enhance operating efficiency and minimize metal manufacturing and mining waste.

Regarding sustainability, Metso promotes circular economy practices such as recycling industrial waste, remanufacturing equipment, and sourcing green materials. The firm has integrated hydrogen-based steelmaking processes and water-saving processes in mining to minimize environmental degradation. Metso's digital strategy includes blockchain traceability of sustainably sourced raw materials. Besides, Metso collaborates with renewable energy producers to create solutions for low-emission industries. While it targets closed-loop material management and process optimization through artificial intelligence, Metso will revolutionize sustainable heavy industry in the future.

Rockwell Automation was established in 1903 in the USA. Currently, the company is involved in industrial automation, digitalization, and intelligent manufacturing processes. It has a presence in over 80 countries with around 28,000 employees and a turnover of €7.8 billion in 2023. Rockwell Automation expanded its business to Finland in 1985. Rockwell leads in AI-driven robotics, IoT-driven industrial control systems, and cloud-based automation software. It uses machine learning and real-time analytics to maximize manufacturing productivity, optimize energy use, and reduce waste. As an early adopter of sustainable manufacturing, Rockwell combines digital twin technology and predictive maintenance to minimize downtime and carbon footprint. In terms of the circular economy perspective, Rockwell also encourages circular economy behavior by initiating automated recycling loops and material reuse in industrial processes. Rockwell works with competent city developers and manufacturing companies to design carbon-neutral manufacturing facilities. Rockwell is one of the leading proponents of global sustainability initiatives and digital supply chain innovations, with a strong energy efficiency and digitalization focus, and it is looking for innovative ideas for more advanced digital supply chains and global sustainability. Rockwell is future-proofing AI-based predictive diagnostics and blockchain traceability to further enhance sustainable manufacturing and industrial automation.

Schneider Electric was founded in 1836 in France. The company is well-established in energy management, industrial digital transformation, and automation. Schneider Electric operates in more than 100 countries. They have employed approximately 150,000 staff members and had a revenue of €35.9 billion in 2023. Schneider Electric entered the Finnish market 1975 to further enhance its business in the country's industry and energy sectors. The organization leverages AI, IoT, and blockchain for its intelligent energy solutions to maximize energy usage and improve sustainability. It created digital twin technology and predictive analytics to enhance industrial efficiency and minimize waste. Schneider Electric has set 2050 as the year for net-zero carbon emissions and is investing in renewable resources, circular business models, and smart manufacturing. It has also proposed closed-loop material reuse for large industrial projects and energy management automation for industrial industries. Schneider Electric is also active in smart cities and implements AI-driven grid management and energy optimization solutions. Its EcoStruxure™ solution combines global cloud-connected monitoring, automation, and real-time sustainability monitoring across enterprises. Schneider Electric collaborates with governments and international industries to develop low-carbon, energy-efficient infrastructures to enable a sustainable future.

UPM is a Finnish-origin company that provides sustainable and renewable alternatives to products made from fossil-based products. The company was formed in 1996 when several forestry companies in Finland merged. In 2023, UPM reported €10.5 billion in revenue. According to a 2023 report, the company employs 16,573 people and operates in 12 countries worldwide. The company works on circular bioeconomy solutions, promoting sustainable forestry, responsible water use, and environmentally friendly manufacturing. UPM achieves transparency in supply chains through digital technology and artificial intelligence. This includes using blockchain to track materials and the Internet of Things (IoT) to monitor resources. Sustainable labeling solutions are developed by UPM Raflatac, and biodegradable packaging materials are created by UPM Specialty Papers.

Regarding energy, UPM operates one of Finland's most significant CO_2-free power generation systems, utilizing hydropower, nuclear power, and bioenergy. The biorefinery projects at UPM have established them as front-runners in the biochemicals and biofuels industries among the competitors. Their wood products are being developed as substitutes for plastics and fossil fuels. Following the goal with the UN's Sustainable Development Goals (SDGs), UPM intends to achieve its sustainability objective of creating zero net carbon emissions by the year 2040. With an unwavering commitment to developing environmentally friendly solutions for a brighter future, UPM shows no signs of slowing down.

Mirka is a Finnish company specializing in surface finishing solutions. It was founded in 1943. The company manufactures various applications, such as abrasives, tools, and polishing systems. Mirka is doing its business operation in over 100 countries, providing products and services to customers worldwide. It has a workforce of approximately 1,600 employees across its international operations worldwide. In 2023, the company reported a revenue of €392 million, reflecting its strong market presence. The company focuses on innovation and sustainability, and Mirka continues to advance in eco-friendly manufacturing and digitalized production processes. Mirka focuses on circular economy and sustainability by implementing recycled and sustainable materials in production. It established energy-efficient plants and followed IoT-based process optimization to ensure less wastage and high efficiency. Its carbon-free manufacturing practices and processes involving waste-to-energy conversion work in favor of cutting down carbon prints. Mirka is also making its supply chain more efficient and sustainable. Mirka applies computerized quality checking to deliver high-quality products. It has put in place real-time production monitoring to track manufacturing activities precisely. AI logistics assist in streamlining business and minimizing the wastage of materials. Mirka works with market leaders to develop cleaner and greener manufacturing processes. It is engaged in creating closed-loop recycling systems to reduce environmental footprints. In the process, Mirka continues to advance green and effective practices. Further, Mirka is investing in automation finishing technologies to improve accuracy while reducing material consumption. Embracing innovation and sustainability to a large extent, Mirka continues to transform the abrasive sector through cleaner production processes and products.

Data from 18 corporate reports from 2022–2023 was collected to capture emerging industry trends, digital innovations in supply chain management, circular economy strategy, and the diverse business sectors these companies represent, as outlined in Table 1 below.

Table 1 Company data

Company,	Turnover (2023),	Title of Report	Nr. of Pages,	Founded	Field of Business,
Danfoss,	10.3 B EUR,	Sustainability report; Annual report,	20,	1933,	Industrial Automation,
Nokia	24.9 B EUR	People and Planet Report	140	1865	Telecommunications
Wärtsilä	5.8 B EUR	Annual report	100	1834	Maritime & Energy
Stora Enso	9.4 B EUR	Annual report; Sustainability report	105	1998	Renewable Materials
Logisnext	4 B EUR	Annual report; Sustainability report	75	N/A	Logistics
Capgemini	22.5 B EUR	Integrated Annual Report	220	1967	Consulting & IT
Posti	1.6 B EUR	Sustainability report	50	1638	Postal & Logistics
Kone	11 B EUR	Sustainability Supplement	90	1910	Elevator & Escalator Solutions
Valmet	5.5 B EUR	Annual review	110	1951	Process Technologies
Wipak	400 M EUR	ESG Report	60	N/A	Sustainable Packaging
Huhtamäki	4.2 B EUR	Annual report	85	1920	Packaging
ABB	32 B EUR	Sustainability report	200	1988	Industrial Automation
Vaisala	552 M EUR	Annual report	55	1936	Environmental Measurement
Metso	5.3 B EUR	Financial Review	145	1999	Mining & Aggregates
Rockwell Automation	7.8 B EUR	Annual report	120	1903	Industrial Automation
Schneider Electric	35.9 B EUR	Sustainability report	230	1836	Energy Management
Mirka	392 M EUR	Sustainability report	40	1943	Surface Finishing
UPM	10.5 B EUR	Annual report	180	1996	Bio-based Materials

3.4 Thematic Data Analysis Approach

The research uses thematic analysis as the primary procedure for discovering, investigating, and analyzing patterns (themes) in qualitative data (Braun & Clarke, 2006). Thematic analysis has traditionally been described as having a systematic but flexible approach, which suits investigating circular economy (CE) strategies and digital supply chain management content transcripts and analyzing sustainability reports. This approach allows researchers to systematically discover the contribution of new technologies, sustainability efforts, and waves of digital change across industries (Nowell et al., 2017; Vaismoradi et al., 2013).

The key advantage of thematic analysis is that it is flexible and allows it to compare sustainability practices, reporting structures, and technological implementations across various organizations and sectors (Guest et al., 2012). Due to the different ways companies report on their sustainability, thematic analysis helps to find patterns and differences in how they use digital technologies and circular economy ideas through their supply chains (Clarke & Braun, 2017). This method also allows for an iterative and reflexive process, where themes can be refined and restructured as deeper insights emerge from the data (Terry et al., 2017).

According to Braun & Clarke (2006), thematic analysis follows a six-phase process, as outlined in Table 2.

Table 2 Thematic analysis framework (Braun & Clarke 2016)

Phase	Description
1. Familiarization with the data	Reading and re-reading sustainability reports and interview transcripts to gain a deep understanding of the content.
2. Initial coding	Identifying key concepts and recurring patterns related to CE, digital transformation, and sustainability.
3.Theme identification	Grouping similar ideas and concepts into broader themes based on emerging patterns.
4. Reviewing themes	Refining and ensuring consistency in theme categorization by revisiting and validating initial themes.
5. Defining and naming themes	Assigning final thematic categories and providing clear definitions for each theme.
6. Reporting results	Linking findings to research objectives and theoretical frameworks, presenting interpretations and conclusions.

This six-step thematic analysis procedure offers a rigorous, systematic, and replicable method of coding company sustainability reports and content data to enhance the findings' credibility, reliability, and depth (Braun & Clarke, 2021). Once the thematic analysis is completed, the five most important themes will be utilized to code the sustainability reports, each capturing a fundamental aspect of digital supply chain transformation and circular economy approaches (see Table 3). These problems have been confirmed through the comprehensive review of current literature, industry reports, and preliminary document analysis, addressing current theory and practice opinions on corporate sustainability.

Table 3 Key themes for thematic analysis

Key Themes	Area of focus
Adoption of Digital Technologies	IoT, blockchain, AI, big data analytics, digital twins, additive manufacturing, cloud computing
Supply Chain Transparency	Blockchain-enabled traceability, AI-powered monitoring, data security in supply chain
Circular Manufacturing Integration	Closed-loop production, digital twins for sustainability, material recovery, waste reduction
Challenges in Implementation	Financial, regulatory, technical, and organizational barriers to digital and circular transformation
Future Directions and Innovations	Emerging trends, AI-enhanced sustainability solutions, next-generation supply chain technologies

The content transcripts and sustainability and annual reports will be coded and analyzed systematically according to the thematic analysis framework guided by Braun and Clarke (2006). Rather than being dictated by preexisting theories, the themes will be discovered inductively, meaning insights will be drawn directly from industry practices. Following this framework, the organizational use of digital technologies to further circular economy goals can be better understood using this data-driven approach. Furthermore, the analysis will highlight industries' opportunities and challenges when adopting digital transformation strategies for sustainable supply chain management, providing a comprehensive perspective on corporate sustainability efforts.

4 Results

This chapter examines the main findings from analyzing corporate sustainability reports, annual reports, and other reports. It explains how digital technologies boost circular economy (CE) strategies through digital supply chains. The results are structured around key thematic categories identified through thematic analysis (Braun & Clarke, 2006). These themes illustrate the role of emerging technologies such as AI, IoT, blockchain, digital twins, big data analytics, cloud computing, and additive manufacturing in promoting sustainable supply chain practices.

By comparing 18 company sustainability reports across various industries—manufacturing, logistics, energy, packaging, and technology- this study identifies patterns in adopting digital technologies in supply chains, supply chain transparency, circular manufacturing, implementation challenges, and future sustainability directions. The results contribute to addressing the research question:

What are the key opportunities and challenges in implementing digital supply chain technologies, and how can these technologies be integrated to achieve circular economy goals?

4.1 Adoption of Digital Technologies in Supply Chains

Analyzing sustainability and annual reports of the 18 selected companies repeatedly emphasize exploiting Industry 4.0 or new technologies—such as the Internet of Things (IoT), Artificial Intelligence (AI), Big Data analytics, digital twin simulation, additive manufacturing (3D printing), and cloud computing—to enhance supply chain efficacy. For instance, Schneider Electric's 2023 report reveals some considerable investments in IoT sensors, AI analytics, digital twins, cloud platforms, and big data—all aimed at boosting efficiency and cutting down on environmental impact. They use IoT-enabled sensors and AI-driven analytics to monitor equipment in real time, which helps reduce downtime and extend asset life. ABB also embeds AI, IoT, and cloud-enabled analytics into its electrification and automation offerings to deliver energy-efficient, data-driven operations. In reality, ABB has created Smart Sensor IoT products that monitor machinery energy consumption and performance in real-time, and it uses digital twin models of industrial processes to enable real-time decision-making to improve material and energy efficiency. These images are part of a broad trend: businesses place networked sensors and AI/ML models on manufacturing and logistics networks to collect big data and improve processes (e.g., predictive maintenance, demand planning, or dynamic routing) for increased efficiency and sustainability. Digital twin technology and simulation software adoption are other typical patterns. Like Rockwell Automation, these businesses use digital twins to replicate factory and supply chain conditions, detect inefficiencies, and reduce material wastage before making physical modifications.

This virtual simulation of operations enables circular objectives by uncovering the potential for resource-saving in the manufacturing process of the companies. Some companies are also investigating additive manufacturing (3D printing) as a component of their digital supply chain arsenal, frequently with sustainability in mind. UPM, for example, created wood-based bio composites compatible with 3D printing and demonstrated how demand-driven additive manufacturing can produce high-value products (such as bio-based musical instrument parts) from renewable raw materials. KONE also tests 3D printing to make on-demand spare parts, minimizing unnecessary inventory requirements and waste. These cases demonstrate how digital manufacturing can help a circular economy by allowing localized consumption and production of recycled or bio-based inputs.

On the other hand, cloud computing infrastructure enables many of these developments since firms utilize it to manage enormous data streams from IoT devices and AI-driven analysis. Various reports (e.g., Mirka and Posti) indicate that cloud-based solutions are central to real-time data and analytics sharing in production and logistics. In short, digital technology adoption is ubiquitous: From heavy machinery manufacturers to packaging experts, companies are using IoT networks, AI and analytics engines, cloud infrastructure, blockchain, and even robotics and automation to build more intelligent supply chains. This is part of a more significant Industry 4.0 mentality where consolidated, data-driven processes are optimized and made more sustainable. With the integration of digital functionality, firms establish the technological foundation for more transparent, cyclical, and responsive supply chains.

A brief overview of the essential digital technologies adopted by companies is shown in Table 4.

Table 4 Adoption of key digital technologies

Company	AI	IoT	Blockchain	Digital Twin	Additive Manufacturing	Big Data Analytics	Cloud Computing
Danfoss	Yes	Yes	No	Yes	No	Yes	No
Nokia	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Wärtsilä	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Stora Enso	No	Yes	yes	Yes	No	Yes	Yes
Logisnext	Yes	Yes	Yes	No	No	Yes	Yes
Capgemini	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Posti	Yes	Yes	Yes	No	No	Yes	Yes
Kone	yes	Yes	Yes	Yes	Yes	Yes	Yes
Valmet	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Wipak	No	Yes	Yes	Yes	Yes	Yes	Yes
Huhtamäki	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ABB	Yes	Yes	yes	yes	No	Yes	Yes
Vaisala	Yes	Yes	Yes	Yes	No	Yes	Yes
Metso	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Rockwell Automation	Yes	Yes	Yes	Yes	No	Yes	Yes
Schneider Electric	Yes	Yes	yes	Yes	No	Yes	Yes
Mirka	No	yes	No	Yes	Yes	Yes	Yes
UPM	Yes	yes	Yes	Yes	Yes	Yes	Yes

4.2 Supply Chain Transparency through Digital Tools

Analyzing all the data obtained from the sustainability and annual reports and developing transparent and traceable supply chains are priorities for sustainability throughout the companies. Businesses are utilizing technologies such as blockchain, smart sensors, and AI tracking to obtain visibility from raw material sourcing to final product and, in the process, improve accountability and trust. Schneider Electric's report illustrates applying blockchain ledgers to establish tamper-evident, unchangeable histories of product life cycles that allow stakeholders to track materials from extraction to end-of-life. This blockchain traceability guarantees that sustainability information (e.g., the component's source or the carbon footprint) cannot be changed, thereby building trust in reporting. Rockwell Automation also says blockchain is needed to ensure responsible sourcing and compliance across its global supply chain, with clear records of every transaction or transfer. In transportation, Posti (Finnish delivery and postal company) cooperated with an emissions monitoring program on blockchain technology to enhance carbon data's traceability on supply chains. These instances resonate with a greater understanding of how trust, traceability, and transparency are essential to sustainable supply chain management, as explained in full in the literature.

Aside from blockchain, companies are employing real-time information systems and artificial intelligence to monitor supply chain sustainability metrics. Rockwell's article cites AI-based monitoring technology that allows business to track their use of energy and emissions throughout the supply chain in real-time. Real-time monitoring will enable companies to detect inefficiency or hotspots (i.e., a hot supplier producing excessively high emissions) and address them in advance. Most businesses have strong supplier sustainability programs supported by digital solutions. ABB, for example, employs big-data analytics within a "Sustainable Supply Base Management" initiative to quantify supplier risk and ESG adherence to cover 80% of high-risk spending through such initiatives by 2030. It also employs IoT-based platforms to monitor suppliers' emissions and inform decarbonization strategies. Vaisala's report stipulates how 91% of its suppliers were assessed based on ESG aspects through digital data gathering and scoring (to achieve

100%). Similarly, Posti audits compliance by the suppliers digitally and reports that 92.8% of suppliers comply with its code of conduct. These initiatives demonstrate how data systems enhance transparency into upstream practices, having the ability to ensure suppliers are maintaining ethics, labor, and environmental standards by routinely gathering and analyzing performance data.

Cybersecurity and the integrity of data are the regulators of transparency. Some companies highlight how data security is paramount with supply chain digitization to assure stakeholders of their trust in the information. Rockwell directly sets out cybersecurity as one of the foundations of supply chain transparency and announces that it has introduced AI-driven security solutions to protect digital infrastructure and data integrity. Schneider and ABB also recognize the worth of investing in strong data protection and cyber defenses as they digitize supplier and logistics information. A secure digital backbone avoids data breaches or tampering that can invalidate the integrity of traceability systems. In practice, this means uncompromising access controls, blockchain tamper-resistance, and real-time monitoring for threats on the network. In short, supply chain visibility is being boosted through blockchain traceability, real-time tracking and monitoring, and safe data management. These solutions provide businesses and their stakeholders end-to-end transparency into the origin of materials and social and environmental conditions on the value chain, meeting the escalating demand for precise, end-to-end supply chain insights. The literature on sustainable supply chains emphasizes that such openness, facilitated by digital technology, can improve performance and accountability by a considerable margin and that corporate practices have adequately evidenced this.

4.3 Circular Manufacturing Integration

Each of the 18 companies illustrates measures to integrate principles of circular economy into production and supply chain practices, frequently supported by digital technologies. The thread involves closed-loop production, material recovery and recycling, product life, and minimizing waste. Shared practice is product and process design for circularity. Take KONE's sustainability report, for example. It notes that their elevators are built to be quickly removed and upgraded. This way, they can swap out parts and recycle materials instead of scrapping the whole system. Nearly 90% of what goes into KONE products can be recycled. In addition, they are working with their suppliers to boost the use of recycled materials without affecting quality. Such circular design is frequently data-informed: Firms perform Life Cycle Assessments (LCA) and employ digital product models to identify environmental impacts and where to replace materials or enhance recyclability. ABB, for example, targets 80% of its product range to conform to defined circularity standards by 2030. Moreover, it employs LCA tools to estimate impacts from production through end-of-life disposal. With these outcomes, ABB has developed take-back and remanufacturing schemes – customers return used equipment, which is upgraded or refurbished by ABB, maximizing product life and minimizing the use of virgin material. Rockwell Automation also offers Industrial Automation Repair Services. It monitors the sustainability payback of remanufactured parts (e.g., how much e-waste is prevented), actively encouraging repair instead of replacement to save resources. These instances represent closed-loop supply chain practices: materials are retained in use through maintenance, reconditioning, and recycling as a replacement for disposing of waste after one lifecycle.

Digital technologies play a supportive role in integration in circular manufacturing. Predictive maintenance through IoT and AI technologies is widely used to maximize equipment life and reduce waste. Schneider Electric indicates that its predictive maintenance technologies, through AI, enable industrial assets' operating life extension, lowering the production rate of new replacements. KONE 24/7 Connected Services uses IoT sensors to remotely monitor elevator performance and anticipate maintenance requirements ahead of time, enhancing safety, extending the life of the equipment, and reducing resource usage. Its data-driven solutions ensure the replacement of parts only when they are genuinely needed and that costly failures, typically complete replacement types, are avoided. Circular benefits are also maximized by minimizing waste and ensuring optimality for processes through digital twin solutions. Schneider creates digital replicas of its supply chain operations to mimic and forecast the sustainability effects of varying conditions. It aids in scheduling more effective production cycles or logistics routes that reduce fuel consumption and waste creation. UPM utilizes digital modeling for product design, an example being its pilot on digital product passports for material labeling. It serves as a digital twin of a product's sustainable history with deep data housed that can be recycled or reused at the end of life. By digitalizing a product's composition and environmental impact, UPM can enable correct material recovery when disposing of a product, thereby closing the loop. Certain companies also refer to waste reduction and resource utilization programs in their operations, usually through the assistance of digital tracking. Schneider removed single-use plastics from packaging and attained 63% use of sustainable (recyclable or biodegradable) packaging. Huhtamaki, a manufacturer of packaging materials, launched a new line of recyclable flexible packaging (blueloop™) as a substitute for multi-layer plastics and increased the use of fiber-based packaging to minimize plastic waste. End-to-end tracking of material movement through electronic eyes exposes hotspots of waste, such as Mirka, which employed a cloud-based logistics application to track shipping in real-time and reduce the usage of air freight by 30%, eliminating unnecessary expedited shipping and emissions.

In manufacturing, organizations such as Vaisala report applying smart factory automation (AI calibration equipment, robotics) to improve accuracy and minimize wastage. Vaisala even manufactured biodegradable material for one of its products (a weather radiosonde), saving 66% of plastic through its circular design initiative. Heavy industry actors concentrate on recycling by-products: Metso's mining equipment division, for example, recycles life-expired wear components and encourages recycling material from mine sites. Metso also uses water recycling technologies for mineral processing to limit water wastage. These measures, although industry-specific, all concentrate on the same objective – conserving resources and designing out waste. The idea of a closed value chain, in which outputs become inputs through reuse or recycling, is powerfully at work with these firms. Most notably, partnerships are highlighted as driving circularity; UPM developed an ecosystem program (Beyond Circularity) with 21 partner projects in 2023 to construct new low-carbon circular solutions for its business segments. Mirka is involved in a cross-industry partnership (the SHAPE project) for circular economy innovation and net carbon-negative production through collaborative innovation in recycling, remanufacturing, and digitalized value chains. This collaboration means that circular production typically includes more than one firm – there is coordination across industries, sometimes facilitated by digital platforms for data sharing. Overall, the supply chain implementation of a circular economy is articulated through manufacturing operations, end-of-life processing, and product design. At the same time, digital solutions enable the monitoring, feedback loops, and optimization needed to make circular strategies successful.

4.4 Challenges in Implementation

While significant progress has been made, analyses of the reports candidly acknowledge persistent obstacles and challenges in integrating digital technologies and advancing circular supply chain transformations. They are financial, technical, regulatory, and organizational in nature, usually interconnected and cross-industry. One of the main issues is the high cost and investment to apply advanced technologies on a large scale. ABB and Schneider say implementing IoT, AI, and blockchain technologies in global operations and supply chains will require vast amounts of capital. Junior partners or other suppliers may lack the capital or technical expertise to implement the technologies, leaving a weak link in the chain. Economic uncertainty exacerbates the problem: Huhtamaki said inflation and economic recessions worldwide have made green innovation investments a short-term hurdle. Therefore, even if the long-term ROI for digital sustainability initiatives is positive (due to efficiency improvements and risk mitigation), securing up-front funding and enabling all stakeholders to engage remains challenging.

Regulatory and market challenges form another category. Sustainability regulations vary widely across countries and are rapidly evolving. Due to differing regional regulations, Schneider’s report notes the difficulty of implementing standardized digital-circular models globally. Companies must juggle new compliance requirements such as carbon reporting rules, extended producer responsibility laws, or digital product passport mandates. Rockwell has noted that complexity in managing carbon emissions regulations, data privacy legislation, and other compliance matters across various jurisdictions can impede implementation or necessitate complex solutions (and it has begun to provide AI-driven tools for compliance assistance). Market conditions are also in transition: UPM explained how digital disruption redefines demand trends (e.g., reduced demand for graphic paper, growing demand for sustainable packaging), forcing the company to adapt its supply chain and product mix quickly. Responding to such transitions is a strategic issue, requiring more flexibility than conventional operations can deliver.

Additionally, some technologies are not ready for the market yet for all companies, as they are unsure how to utilize them. For instance, UPM mentioned that they have not rolled out blockchain or digital twins in their manufacturing process yet—probably because the return on investment (ROI) is still a question mark, or maybe these techs are too new for their field. This shows that companies are cautious; they are likely to hold off on fully welcoming new tech until it proves its worth or until industry standards are more firmly established.

The most critical issues will be organizational and human. The most common theme is the necessity of upskilling the workforce and cultural transformation to execute digital transformation effectively. The reports from UPM and Rockwell emphasize that the workforce requires new skills and attitudes to leverage AI, data analytics, and other digital technologies. UPM has invested in training operators and introduced online learning platforms to build "digital capabilities" within employees, embracing change management as inevitable. Rockwell also partners with schools to bridge the skills gap between advanced manufacturing requirements, quoting that the best technology in place will never achieve its full capability unless qualified individuals are available. Having suppliers and partners on board is another organizational concern. ABB reported that not everyone can move quickly to meet its requirements for sustainability technologies, so it has to try to work with programs and even offer cash as an incentive to get them underway. KONE observed that massive stakeholder involvement (logistics providers, regulators, suppliers) is required for a fully sustainable, digitalized supply chain, suggesting coordination effort and expense are not spare change. In reality, human and inter-organizational preparedness needs to complement technical solutions. This finding is consistent with theoretical arguments that management commitment, capabilities, and stakeholder involvement are crucial to adopting digital-circular projects. The absence of top management commitment or inadequate capabilities can threaten projects despite the potential of the technology. Firms recognize these soft barriers and seek to eliminate them through the change management process, partner stakeholders, and training schemes, but continue to experience recurring difficulties. More often than not, repeated investment, learning, and industry collaboration with mutual knowledge diffusion and cost deflation will have to overcome such barriers.

The challenges the company faces in adopting a digital supply chain are briefly outlined below in Table 5.

Table 5 Challenges faced in digital supply chain adoption (By Company)

Company	Primary Challenge
Danfoss	Financial
Nokia	Technical
Wärtsilä	Regulatory
Stora Enso	Organizational
Logisnext	Regulatory
Capgemini	Organizational
Posti	Financial
Kone	Financial
Valmet	Technical
Wipak	Regulatory
Huhtamäki	Organizational
ABB	Technical
Vaisala	Financial
Metso	Technical
Rockwell Automation	Organizational
Schneider Electric	Regulatory
Mirka	Financial
UPM	Organizational

4.5 Future Directions and Innovations

The sustainability reports give us much hope for the future. Companies are stepping up their digital and circular efforts, setting bold targets, and some exciting innovations are coming. A big focus for the future is a closer partnership between AI and advanced analytics to boost sustainability. Many firms plan to expand AI-driven optimization in operations. For example, ABB is developing AI-powered sustainability analytics to forecast energy consumption better and optimize performance as it works toward a net-zero emissions goal by 2050. Rockwell is also investing in next-generation AI for automation and predictive insights to further reduce environmental impact in manufacturing. We see an expectation that machine learning will increasingly help companies predict and prevent sustainability issues (like equipment inefficiencies or supply disruptions) before they happen, effectively making supply chains more "self-optimizing." Digital twins are slated for broader use in this predictive, scenario-testing capacity. ABB wants to use digital twin modeling to better use resources across its global operations.

On the other hand, Rockwell intends to use digital twins for more in-depth supply chain simulations to find opportunities for the circular economy and reduce resource use. In real life, this could mean that every critical product or process has a virtual copy that managers can use to find the greenest and most efficient ways to set up. This concept fits the new "smart factory" and "Supply Chain 4.0" paradigms.

Another prominent future theme will be better supply chain transparency and data sharing among the stakeholders. Companies are preparing for increased demands for detailed sustainability info from customers, regulators, and others. To meet this need, they are working on digital solutions. A great example is UPM, which is developing a prototype for a digital product passport. This is a sneak peek of what is on the horizon, as the company plans to roll these passports out more widely once new regulations, like the upcoming EU requirements, are in place. With these passports, people can easily access a product's sustainability information throughout its lifecycle. We may see widespread use of QR codes or blockchain-based certificates accompanying products containing data on origin, carbon footprint, material composition, and end-of-life instructions. Several reports suggest exploring blockchain or other decentralized ledgers further to ensure this information is tamper-proof and easily shared among partners (even though not all have implemented it yet, interest remains high).

Additionally, companies are bringing supplier monitoring together onto a single digital platform. For instance, UPM kicked off a "Sustainable Supply Chain Programme" in 2023 that uses digital KPIs to monitor supplier performance and is looking to boost the percentage of spending managed by these systems, which is already at an impressive 89%. This indicates future supply chains will likely feature tighter digital integration with suppliers, more significant data transparency upstream, and possibly mandated reporting of Scope 3 (supplier) emissions as part of climate targets (indeed, Vaisala notes that over 99% of its emissions are in the supply chain and is committing to science-based Scope 3 reductions)

In the context of circular economy innovation, all firms are exploring material and energy limits. All of them invest in R&D expenditure in environmentally friendly technologies. Metso increased its R&D expenditure (€73 million in 2023) in the processing of battery minerals, automation, and artificial intelligence solutions, and will continue to build more electrified and hydrogen-ready industrialized equipment in the future part of its portfolio. This is one aspect of a trend in product development to keep up with the clean energy revolution – i.e., equipment that can be powered by renewable electricity or hydrogen fuel to facilitate low-carbon, circular business for customers. Some firms (ABB, Schneider, Rockwell) mention exploring renewable energy and carbon reduction technologies. Rockwell is developing carbon capture and storage solutions and leveraging AI to improve the adoption of renewable energy in the industry. ABB is introducing high-efficiency electrification products and even hydrogen-powered solutions to cut emissions. We also see an emphasis on electrifying transport and logistics: Posti is expanding its electric vehicle fleet (integrated with IoT fleet management) to cut delivery emissions, and others likely will follow suit as technology and infrastructure improve. Companies like KONE plan to keep using 3D printing for spare parts. They are making their products more modular and upgradable to support longer lifecycles, so additive manufacturing and circular design are still front and center. By printing only what is needed, where it is required, these practices have the potential to significantly decrease waste and give rise to new circular business models, such as localized production hubs for remanufacturing parts. The notion of Circular Economy 4.0, where digital tech and circular principles jointly transform value chains, is becoming tangible in these forward plans. Academic discourse suggests that such integration of Industry 4.0 tools with circular models can unlock new levels of sustainability performance, and the companies in our sample appear to be on that trajectory.

Collaboration and ecosystem-building are also significant parts of future strategies. Companies know they cannot change the system independently, so many are teaming up with other companies in the same field, tech companies, and even governments. Schneider Electric's report notes collaboration with industry bodies to develop standard frameworks for digital sustainability solutions. Rockwell is forming strategic partnerships with renewable energy providers and participating in global initiatives (like the World Economic Forum's circular transformation projects). Huhtamaki is partnering with sports organizations and waste management firms to pilot event zero-waste solutions, linking circular practices with community engagement. Mirka's participation in the multi-firm SHAPE project (with public co-financing) is just one example of how cross-industry ecosystems are evolving to exchange knowledge and accelerate green innovation. This examines literature that points to supply chain coordination and cooperation as core drivers of successful digital-circular change. More open platforms and consortia are what we might expect, with companies sharing data (maybe using cloud exchanges or blockchain networks) to improve traceability or co-invest in recycling plants, which benefit all involved.

Ultimately, businesses consistently reinforce their long-term sustainability commitments and the contribution of digital technology to making them possible. Almost all of them have set carbon neutrality or deeply reducing emissions targets (e.g., net-zero by 2030 or 2050) and growing circular use of materials by some target dates. Achieving those goals will inevitably involve ongoing innovation. For example, Schneider is expanding its resource recovery efforts and investing further in additive manufacturing to reduce waste. Vaisala is growing its cloud-based solutions (such as the Xweather platform) to offer environmental intelligence that can support whole industries in cutting emissions and adapting to climate threats. The general consensus is that digitalization is not a single project but a continuous process. Next-generation supply chains will be more intelligent, automated, and circular in nature. As was stated in one report, the management is aware that advanced IT systems "enable efficient operations and optimized performance, as well as new customer services" – a positive sentiment behind continued investment in digital platforms, AI, automation, and data exchange to support greater sustainability. Companies align their innovation roadmaps with the dual goals of competitiveness and sustainability. This reflects theoretical arguments that dynamic capabilities in the digital age – the ability to continually integrate new technologies and adapt business models– will determine firms' success in advancing circular economy outcomes. In the next ten years, intelligent supply networks and circular economy practices will likely become the norm. Through AI-enhanced decision-making, real-time transparency, and collaborative innovation, the "next generation" of supply chain technology promises to make things more efficient and help reach global sustainability goals in ways that have never been seen before.

4.6 Summary of Key Findings

The outcomes of the current research study present an in-depth analysis of the role of emerging digital technologies in digital supply chains in implementing a circular economy strategy. By analyzing the content of 18 multinational companies' sustainability reports, essential conclusions have been drawn about technological adoption, transparency, circular manufacturing, challenges in implementation, and future innovations. Thematic analysis reveals that businesses are increasingly utilizing AI, IoT, blockchain, cloud computing, big data analytics, digital twins, and additive manufacturing to maximize the use of resources, improve traceability, and minimize supply chain waste, although some businesses do not utilize this technology in their supply chain. Still, they have this technology in their company in other areas, which can also be used in the supply chain.

Both opportunities and challenges encourage the circular economy. While emerging digital technologies support automation, predictive maintenance, and sustainable resource management, financial, regulatory, technical, and organizational barriers limit extensive take-up. In addition, sectors like manufacturing, logistics, energy, and packaging have varying digital maturity in embracing circular economy practices.

This section presents a summary of key findings derived from thematic analysis, categorized under five primary themes presented in Table 6.

Table 6 Summary of key findings

Theme	Key Findings
Role of DT	Companies such as Schneider Electric, ABB, and Rockwell Automation extensively integrate IoT, AI, digital twins, and cloud computing to optimize supply chains. Valmet and Wärtsilä leverage big data analytics for predictive maintenance. UPM and KONE use additive manufacturing for on-demand production, reducing waste.
Transparency	Blockchain-enabled traceability is being used by Stora Enso, UPM, and Rockwell Automation to enhance supplier accountability and product tracking. AI-powered monitoring by KONE and Metso improves operational efficiency. Companies highlight cybersecurity as a key challenge in digital transformation.
Waste Management	Companies like Mirka, Huhtamäki, and Wipak focus on closed-loop production, sustainable packaging, and material recovery systems. ABB and Wärtsilä integrate digital twins for resource efficiency and waste reduction. AI-driven predictive maintenance extends equipment life cycles and minimizes waste.
Challenges	Financial constraints and regulatory barriers hinder digital adoption, particularly for Posti and Logisnext. Technical challenges include data standardization issues (Vaisala), cybersecurity risks (Schneider, ABB), and the need for supplier alignment (KONE, ABB). Organizational resistance to change is a recurring barrier.
Impact Traceability	AI-driven sustainability analytics and digital twin simulations are expanding in companies like ABB and Rockwell Automation. Companies are investing in product lifecycle transparency (UPM's digital product passport, blockchain traceability initiatives). Renewable energy integration and electrification of logistics fleets (Posti) are key future strategies.

5 Conclusion and Discussion

5.1 Conclusion

The research question of this thesis was: What are the key opportunities and challenges in implementing digital supply chain technologies, and how can these technologies be integrated to achieve circular economy goals? This research analyzes how digital supply chains can facilitate the shift toward a circular economy (CE). This research explicitly addresses the contribution of new digital technologies, which are considered emerging technologies or 4.0 technologies, and their application in the supply chain process. The study analyzed how 18 multinational firms doing business operations in Finland leverage technologies such as artificial intelligence (AI), the Internet of Things (IoT), blockchain, digital twins, cloud computing, additive manufacturing, and big data analytics to make their companies more circular, efficient, and transparent. The study also identified the most significant opportunities and challenges for companies to adopt a digital transformation of their supply chain in the circular economy.

The findings demonstrate the widespread adoption of digital technologies in manufacturing and supply chain processes, a process that is influencing supply chain operations. Several opportunities and challenges exist in implementing digital technology in their supply chain to produce a circular economy goal. Among them, key opportunities include using AI and digital twins for predictive maintenance. The application of blockchain technology can enhance traceability. Cloud computing enhances data management and transparency in data sharing among stakeholders. The use of these technologies helps to reduce waste as well as improve resource efficiency and promote closed-loop systems. On the contrary, challenges such as financial limitations, regulatory compliance, technical interoperability, and organizational resistance are indicated, which makes the process slow in many cases. Large companies are leading the digital transformation in their manufacturing processes and supply chains. Still, small and medium-sized enterprises

(SMEs) face difficulties in making digital transformations as they have limitations, which are attributed to limited resources and technical capacity. This study found that broader collaboration, supportive policies, and scalable solutions are needed to enable organizations to adopt digital technology in their supply chains and make the supply chain process compatible with the circular economy.

Regarding the first research objective, to examine the role of emerging digital technologies in promoting circular economy efforts within the supply chain, this research analyzed the company's current situation and how companies adopt and integrate these digital technologies in their manufacturing operations and the supply chain. Research shows that companies such as Schneider Electric, ABB, Rockwell Automation, and Nokia leverage technologies like the Internet of Things (IoT), artificial intelligence (AI), and blockchain to improve transparency, efficiency, and traceability. These companies use IoT to enable real-time monitoring and asset tracking across the supply chain. Conversely, these companies leverage AI to facilitate predictive analytics and enhance their decision-making capabilities. Blockchain enhances trust and accountability by safeguarding transaction records and monitoring material flows. Companies like ABB and Wärtsilä also use digital twins to create virtual models of physical systems. Digital twin allows for better resource planning, maintenance prediction, and waste reduction. Big data analytics helps organizations like Valmet and Metso analyze large datasets to optimize processes and reduce environmental impact. Cloud computing is also gaining traction in companies like Capgemini and Nokia, which enable scalable data sharing, collaboration, and automation across supply chain networks. Furthermore, additive manufacturing, adopted by UPM and KONE, supports on-demand production and minimizes material waste by reducing excess inventory. These emerging digital industry 4.0 technologies are helping companies transition from linear supply chains to digital supply chains to maintain a circular economy and data-driven systems that focus on resource efficiency, closed-loop processes, and sustainable production.

The second objective was to analyze the impact of digital technologies on key sustainability issues, including transparency, traceability, and waste reduction. The study found that companies such as UPM, Stora Enso, and Rockwell Automation, for instance, employ blockchain to validate raw material traceability and maximize supplier responsibility. These digital technologies enable greater product flow and sourcing transparency, allowing for ethical and responsible supply chain management. Metso, Vaisala, Danfoss, and KONE all use AI-based decision-making and monitoring systems to improve operational efficiency, reduce human error, and allow for predictive maintenance. Companies including Schneider Electric, ABB, Nokia, and Wärtsilä are collecting real-time data on equipment performance and environmental variables. This includes energy consumption using smart sensors and connected devices (IoT). This helps them solve problems faster, enhance transparency, and identify difficulties early on. ABB and Wärtsilä, meanwhile, test several approaches to using resources or scheduling repairs using digital twins—virtual copies of machines or systems. This helps minimize the waste of resources and prevent unplanned breakdowns of equipment.

Companies like Valmet and Capgemini rely on data analysis tools to study the vast amounts of supply chain information. These tools enable them to streamline processes, more precisely forecast consumer needs, and prevent overstretching of products, thus minimizing waste. Nokia, Schneider Electric, and Capgemini use cloud computing to improve transparency. It helps them share data clearly and work better with others. UPM, KONE, and Mirka use additive manufacturing. This helps reduce waste by making products only when needed. Huhtamäki and Wipak focus on reusing or recycling packaging using digital technologies. They use digital tools to support waste reduction. Posti and Logisnext use digital systems to lower emissions and manage returns better. This also helps with waste reduction. All 18 companies use digital technologies to improve transparency. These digital tools also make traceability better. As a result, companies can track their materials and work to reduce waste in their supply chain processes.

The third objective was to define a best practice for organizations undergoing digital transformation to implement a circular economy. The study found that the best results come when companies use many digital technologies together. For example, ABB and Rockwell Automation use AI, IoT, cloud computing, and digital twins at the same time. This helps them create smart, transparent, and sustainable supply chains. A successful plan starts with checking if the company is ready for new technology. Training employees is also very important. Companies should improve cybersecurity and ensure their digital tools match circular economy goals. Successful companies bring different teams together. These include sustainability, IT, operations, and purchasing. Working together makes the process smoother. The study also shows that industry rules and shared digital platforms can help more companies join the change. Digital transformation makes it easier to adopt circular economy practices. Many large companies are already doing this well. However, smaller companies still need help. Support, teamwork, and better access to technology can help everyone move forward. This will build more substantial and more sustainable supply chains.

In conclusion, integrating digital technologies into supply chain operations plays a crucial role in driving circular economy goals. This study's findings offer valuable insights into how companies leverage these technologies to enhance sustainability and operational efficiency. They also emphasize the practical challenges that need to be addressed to ensure digital transformation is accessible and effective across various organizational contexts.

5.2 Discussion

As we know, validity refers to how well this study measures what it intended. At the same time, reliability indicates how consistent and stable the research results are over time and across different situations. In this thesis, steps were taken to ensure validity and reliability by carefully planning the data collection and analysis process. The research objectives and questions were clearly outlined, and the choice of methods aligned with the study's aims. The study captured how businesses truly operate by examining sustainability reports from 18 different companies across various industries. Secondary sources such as sustainability reports, company disclosures, and annual reports were used to support the findings of this research. This method provided a comprehensive view of how digital technologies assist companies in adopting circular economy strategies within their supply chains. The advancement and application of innovative digital technologies will shape the future of digital supply chains and practices in the circular economy. As industries shift toward smarter, data-driven, and more sustainable supply chains, more research is needed to improve digital adoption strategies, address challenges, and increase the positive impact of these technologies on sustainability. Future studies should explore how digital supply chains can support both business success and environmental goals in the long run. This exploration should include an investigation of the policy and regulatory landscape for digital supply chains, an examination of the Digital Transformation Challenges for SMEs in Circular Economy Supply Chains, and an evaluation of the Impact of Digital Technologies on Circular Supply. Chain Performance, and so on.

This study has limitations because it focuses solely on qualitative content from company reports. Although these documents provide useful information on how businesses plan and implement new technology, they often emphasize the positive aspects while potentially omitting the negative ones. Additionally, while it is clear that many organizations are investing in new technology, it is not necessarily apparent whether they have integrated it into their supply chains just yet. A major shortcoming of the study is that it does not use primary data, which would have provided valuable insights from people working in the field through surveys and interviews. Because digital technology is developing rapidly, some of these conclusions might become obsolete when new innovations and regulations emerge.

Despite its limitations, this study lays a solid groundwork for future research into how digital supply chains can drive circular economy transformations. Future research could greatly benefit from a mixed-methods approach that combines quantitative analysis with direct insights from the industry to add depth to qualitative findings. Additionally, longitudinal studies could help track how digital adoption progresses over time and assess its real-world impact on sustainability efforts. To conclude, this study has simplified the growing importance of digital technologies in supporting circular economy strategies while also navigating the challenges and opportunities that companies encounter as they shift toward sustainable digital supply chains. The results provide valuable insights for business leaders, policymakers, and researchers, showing that blending technological innovation with strategic collaboration and regulatory support can significantly accelerate the transition to a more circular and sustainable economy.

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