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The Role of Digital Technologies for Enabling Circular Economy in E-waste Management - Multi-Level Analysis

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List of Abbreviations/Acronyms

DTs: Digital Technologies

CE: Circular Economy

LE: Linear Economy

E-waste: Electronic Waste

MLP: Multi-Level Perspective

EPR: Extended Producer Responsibility

EEE: Electrical and Electronic Equipment

CEAP: Circular Economy Action Plan

IoT: Internet of Things

AI: Artificial Intelligence

RFID: Radio Frequency Identification

DPPs: Digital Product Passport

EU: European Union

SNM: Strategic Niche Management

TIS: Technological Innovation System

DPA: Danis Producer Responsibility

SMEs: Small and Midsize Enterprises

CSRD: Corporate Sustainability Reporting Directive

EPRI: Extended Producer Responsibility Implementor

1. Executive Summary

Technological development leads to a better life for people; however, producing electrical and electronic equipment in the linear economy (LE) model generates enormous amounts of electronic waste (E-waste) and creates significant environmental problems. Circular economy (CE) is considered an alternative approach to LE to minimize the environmental impact of E-waste. Nevertheless, various factors are essential in the transition toward CE, including digital technologies (DTs). This research aims to explore the impact of digital technologies in the transition towards a CE in E-waste management systems. In addition, this research aims to understand how key non-technological factors such as climate change, policy, social awareness, and market demand impact the transition towards CE in the E-waste management industry. This study used Multi-Level Perspective (MLP) analytical framework to analyze not only the technological but also the interaction of multi-actors in niche and regime and the impact of landscape factors in a sustainable transition. The method is qualitative, and the data was gathered from 10 interviewees, including sustainability experts and actors involved in E-waste management, through semi-structured interviews.

The study discussed the role of DTs in facilitating the adoption of CE principles in E-waste management. The findings suggest that DTs have the potential to enable CE practices in E-waste management but may not serve as the primary driving force in transition. DTs demonstrate the capacity to promote CE principles, including reduce, reuse, and recycling, in the management of E-waste. Moreover, they can enhance stakeholder collaboration, transparency, and business operational efficiency. However, particular challenges were identified, such as limited digitalization and resistance towards DTs adoption within the actors. The research also underscores the impact of various factors on firms' inclination to adopt CE practices, including climate change, policy frameworks, and societal awareness. The Extended Producer Responsibility (EPR) directive positively affected collaboration and recycling practices among actors in E-waste management. Nevertheless, lack of policy enforcement, variations in the implementation of EPR in each country, and ambiguity of actor's responsibility in EPR pose challenges to adopting CE. As a result, the study suggests that policy enforcement and enacting policies mandating information sharing among stakeholders may enhance transparency and collaboration in E-waste management practices to adopt CE principles.

2. Introduction

2.1. Background

For a long time, the socio-economic model has been linear economic (LE), which often described as “take-make-dispose”. In this linear economic model, the flow of material is the logic of value creation in which pure materials enter the beginning of the value chain. LE model is based on extraction, transformation, and disposal, which has numerous problems concerning sustainability, including significant waste, incorrect disposal, excessive emission, and erosion of ecosystems (MacArthur, 2015). According to Kaza et al.(2018), 60 percent of End of Life (EoL) material in Europe is not recycled and reused. The waste generation is increasing by passing every day, and anticipated that it will outpace population growth by more than double by 2050.

E-waste is the fastest-growing waste globally, currently, E-waste generation is approximately 53.6 million metric tonnes in 2019 annually, constituting roughly 8% of the total municipal solid waste generated. Notably, the recycling rates for E-waste remain suboptimal, with less than 20% of this category of waste undergoing recycling processes (*E-Waste Vol. 1: Inventory Assessment Manual*, n.d.). The rapid global escalation in E-waste generation can be attributed to various factors. The accelerated pace of technological advancement and high consumer demand for and reliance on electronic devices for daily usage significantly contribute to this trend. Furthermore, the intricate and often non-durable design of electrical and electronic equipment (EEE) results in products with shortened lifespans. Consequently, the volume of E-waste increases progressively with each passing year (Vishwakarma et al., 2022; Maphosa & Maphosa, 2020). Toxic element in E-waste is very harmful to both the environment and human health; if not properly managed and recycled, these components may lead to air, water, and soil pollutants which can further cause serious issues for human health (Ghulam & Abushammala, 2023). Aside from the negative effects of E-waste on the environment and human health, it is noteworthy that such waste comprises valuable elements that can be extracted, recovered, and repurposed to manufacture new materials. Consequently, the recycling of E-waste carries dual significance. On the one hand, it serves an environmental role by reducing pollution and forestalling the extraction of scarce natural resources. On

the other hand, it embodies substantial economic value, presenting profitable opportunities through recovering and reusing precious materials contained within the waste (Pant et al., 2020).

The aforementioned issues arising from the existing LE model have attracted the attention of governments and policymakers. Their focus has been on addressing waste generation concerns to protect scarce natural resources, slow the rise of global warming, and mitigate the adverse environmental consequences associated with waste disposal. To achieve this goal, governments proposed various sustainable solutions (Uçar et al., 2020), one of the solutions is the CE. This is believed that CE is the answer to the concerning threats and problems and is an alternative solution to a traditional linear economy, “make, use, dispose” (D’Amato et al., 2017). According to Gregson et al.(2015), CE is a prenominate alternative to the traditional “make-use-dispose” due to materials and energy circular follow. CE is a regenerative or restorative industrial system by design that opposes the open-ended system to face challenges of resource scarcity and minimize waste disposal. For instance, what is considered waste in classic LE should be used as input for another industrial process or as a renewable resource for nature (Hobson, 2016).

Numerous countries are working toward introducing policies to promote CE to reduce waste and control climate change and its issues. However, European countries are at the forefront (Shittu et al., 2021). Several EU policies promote CE adoption, including the Circular Economy Action Plan (CEAP), Waste Framework Directive, and the European Green Deal (D’Adamo et al., 2022; Xavier et al., 2021). Those policies cover various aspects like the design and production of products, waste reduction, producer responsibility, and consumer law to achieve sustainability and protect the environment and human health (Šipka, 2021). In the context of E-waste management, the Waste of Electrical and Electronic Equipment (WEEE) Directive aims to enhance the EEE product life span by stressing a modular design. In this way, EEE products should be designed so that components are separable, repairable, and reusable easily. Another aim of the WEEE directive is to reduce E-waste disposal in landfills by increasing the recycling rate (Lauridsen & Jørgensen, 2010). To achieve this aim, Extended Producer Responsibility (EPR), which is part of the WEEE directive, obligates the manufacturers and producers of EEE to take financial responsibility for their E-waste instead of municipalities (Barapatre & Rastogi, 2022). In fact, EPR resulted in emerging of new firms collaborating with

municipalities to manage E-waste. However, each country's implementation methods may differ (Lauridsen & Jørgensen, 2010).

Implementation of CE is challenging because various factors impact on successful implementation of CE. The idea of the CE business model is that one company cannot close the loop, but the ecosystem can. Thus, companies and the supply chain need collaboration, contribution, and cooperation. DTs, especially communication platforms like e-procurement, virtual reality, and AI considered enablers of networking and facilitator of information sharing between stakeholders, including customers (Antikainen et al., 2018). AI, for instance, is being used by firms like Stuffstr to collect used clothes and resell them to consumers by offering dynamic prices to the customer. According to the CEO of Stuffstr, "Enabling pricing of used products is instrumental to boosting product circulation because it both drives people to resell through secondary markets the items they are no longer using and to shift their buying preferences to items that hold their value longer [based on the age of use and brande]. [...]" (Ellen MacArthur, 2019, p.28). Furthermore, only returning the used products by consumers is not essential, but supporting and purchasing the remanufactured products is important. It indicates that consumers have an essential role in transitioning CE in adopting remanufactured, used products alongside the policy impact and the firm's collaboration. In the context of E-waste management, consumers also serve as crucial factors in the reduction and recycling of E-waste, as they constitute the initial point where the lifecycle of E-waste begins. Consumers from the CE perspective can collaborate to reduce E-waste in the following areas, including repairing, reusing, sharing (refurbishment), and recycling E-waste (Islam et al., 2021). The researchers mention that DTs can enable customer communication to adopt better CE and innovative CE business models (Antikainen et al., 2018; Hazen et al., 2017).

2.2. Research problem

As previously articulated, the transition towards a CE presents significant challenges influenced by various contributing factors. Specifically in the context of E-waste, despite government backing and establishing regulatory measures such as the WEEE directive, approximately 54 percent of E-waste is projected to be improperly recycled outside formal channels. This frequently entails illicit exports to developing countries. Conversely, the advent of EPR has initiated the formation of new firms and actors aiming to enhance

E-waste management, a trend particularly noticeable within the EU, but the WEEE directive hase not achieved the goals (Lauridsen & Jørgensen, 2010). However, to overcome CE implementation challenges, among other factors, DTs such as the Internet of Things (IoT), big data analytics, and artificial intelligence (AI) are considered enablers and promoters of CE strategies (Reike et al., 2018).

CE and DTs have essential relations. DTs can boost the transition from the LE model to the CE model, and this is because it has significant potential in various domains of CE. For instance, the IoT can provide accurate information about the availability, location, and condition of products which helps for better monitoring, analyzing, controlling, and easier recycling, especially E-waste (Antikainen et al., 2018). RFID[1] can generate information about goods that the supply chain of the retail industry can use this data to assess the quality of goods and improve return flows across the product life cycle. (Khan et al., 2022). Meanwhile, DTs assists business and firms to become more competitive in the market because DTs allows the firms to provide more creative solutions, lower prices, improve equipment efficiency, and use fewer resources (Kiel et al., 2019). AI is not an exception, according to researchers, it also fits a variety of functions in CE. For example, Schlüter et al. (2021) mention that integrating AI in waste management can improve the identification and inspection of material for sorting and reduce input errors.

DTs have numerous advantages in the domain of CE, and it's attracted the attention of policymakers, practitioners, and researchers. However, there are two problems and research gaps that this research aims to fulfill. First, lack of critical analysis of DTs role as an enabler of CE. This is because, at the time of writing this paper and based on this papers author understanding, analyzing the role of DTs critically and how DTs practically support CE in E-waste management is unexplored. As Khan et al. (2022), suggest for detail and empirical study of DT's relationship with CE. Because, Majority of the studies are theoretical or conceptual (Ghoreishi & Happonen, 2020b; Ramadoss et al., 2018). Additionally, rather than a research gap, many scholars (See, e.g., (Agrawal et al., 2021; Awan et al., 2021; Ghoreishi & Happonen, 2020b, 2020a)) called for empirical studies to expand knowledge about the role of DTs in detail in CE. Secondly, it is essential to emphasize that the transition toward sustainability is a complex process. Instead, it is characterized by its complexity and transformative nature due to several defining aspects.

[1] Radio Frequency Identification.

Such transition is multidimensional in scope, engages a diverse range of actors, and is often subject to uncertainty and discord among the involved actors. Furthermore, sustainability is a long-term initiative that demands sustained effort to accomplish the intended objectives (El Bilali, 2019, 2020). Various stakeholders play a crucial role in E-waste management, shaping the management processes (Lauridsen & Jørgensen, 2010). However, to the best of this paper author knowledge, at the time of writing this paper, no other similar study exists that critically examines the role of DTs and key non-technological factors in enabling the CE within the context of E-waste management through the lens of MLP. Therefore, this research aims to analyze the role of digital technologies (Big data, IoT, AI, blockchain, and digital platforms) and key non-technological factors that impact transforming E-waste management toward a CE (socio-technical transition) by conducting a qualitative study interviewing companies, NGOs and experts involved in managing of E-waste in the European countries. This research focuses on the management level of E-waste, explicitly examining the involvement of different actors in implementing CE practices and the impact of digital technologies. The study also considers key non-technical factors that influence the adoption of CE in E-waste management.

MLP framework has been used for this study as a lens because MLP offers a comprehensive framework to explore complex and multi-level interactions of three analytical levels such as niches (micro level), soci technical regimes (Meso level), and landscape (macro level) levels, by considering not only technological but also societal and institutional value and dimensions to analyze and understand sustainable transition (F. W. Geels, 2018; Schot & Geels, 2008). check the theoretical framework (chapter 4) for more.

2.3. Research question

The primary research questions for this study are:

- How do digital technologies impact the transition towards a circular economy in the management of electronic waste?
- How do key non-technological factors influence the transition toward a circular economy in the electronic waste management system?

2.4. Delimitation

This study focused primarily on the administration level of E-waste to minimize E-waste generation and enhance the recycling of it. Also, various actors are involved in E-waste management, including Extended Producer Responsiblity Implementor (EPRI), municipalities, compliance schemes, and digital solutions providers. Therefore, this study focuses only on the administration level of E-waste. The author assumes that other actors, such as producers of EEE and recyclers, are also playing essential rule. However, this study does not delve into the machinery-focused aspects of the recycling process, such as sorting, shredding, and disposal.

2.5. Structure

This paper includes several chapters, each providing specific information about this research. The "Literature Review" chapter offers insights into the challenges associated with E-waste, explores the potential of CE principles in E-waste management, examines the role of DTs in enabling CE, and investigates the impact of policies on the adoption of CE practices. The "Theoretical Framework" chapter explains the concept of sustainability transition and its multidimensional factors while introducing MLP as a suitable analytical framework for this study. Later, the "Methodology" chapter provides comprehensive information about the methods employed in this study. The empirical findings are presented in the "Empirical Results" chapter, categorized according to the MLP's three analytical dimensions. In the "Discussion" chapter, the study's findings are critically examined in light of existing literature and the MLP framework. Finally, the "Conclusion" chapter summarizes the research outcomes and draws overall implications.

3. Literature Review

3.1. Electronic Waste

Manufacturing companies are producing vast amounts of products in a linear business model based on "take-make-dispose" to meet the need of people, and each of those products become waste in the end (Reim et al., 2021). Also, E-waste is a severe problem; it is increasing immensely daily. This is because of rapid economic growth, technical improvement, and urbanization, which resulted in the enormous usage of electrical gadgets in daily life (Ghulam & Abushammala, 2023). The European Council and Parliament define EEE as equipment used in households or industries operating on electric currents or electromagnetic fields. Examples include medical devices, lighting equipment, information technology equipment, computers, phones, toys, and other leisure items. Such technological development has brought numerous advantages to society and our daily lives; however, one of the significant impacts of enormously using EEE is the immense amount of E-waste (Sengupta et al., 2022). E-waste has become an alarming global issue, specifically after the COVID-19 pandemic when the concept of working from home was introduced and adopted almost by all sectors, which resulted in people's strong reliance on electronic equipment like mobile phones, computers, laptops, and many other (Vishwakarma et al., 2022).

The E-waste definition is different globally, and no unified definition exists. The term E-waste refers to any EEE that is unwanted, outdated, not functioning, or has reached the end of its life but has not been discarded (Purchase et al., 2020). However, according to the European Union WEEE directive, E-waste refers to all EEE that has become waste, including working and broken items, basically all components when discarded (Ghimire & Ariya, 2020). Regarding size, E-waste is divided into two categories: The first one is large devices, also called “white goods”, such as refrigerators and washing machines. The second one is small and personal devices called “brown goods”, such as mobile phones and computers (Ghimire & Ariya, 2020).

The UN anticipated that if the E-waste generation continues with a 5 percent annual growth rate, the global E-waste generation will be doubled and increase to 140 million metric tons by 2050 (Herat, 2021). Historically, in developed countries like the EU, E-waste is increasing by 16 - 28 percent every five years, which is three times more than solid waste. However, in developing countries, the generation rate of E-waste is much

higher. This is because of the less developed technology for managing waste, policy limitation, illegal importing of waste, and high rate of informal waste recycling (UNEP, 2023).

The generation of E-waste is experiencing a rapid and steady increase due to several reasons. To be more specific, technological development leads to people's heavy reliance on EEE, which increases the usage rate of electrical gadgets and E-waste (Vishwakarma et al., 2022). This heavy reliance and current society's fascination with electrical gadgets and the insatiable desire to possess the newest products have resulted in the development of modern electronics that have shorter lifetimes and other complications associated with their complex designs (Ankit et al., 2021). Therefore, the lifespan of computers and peripheral devices has been shortened from 5-10 years to 3-4 years because they are now designed with a priority on replacing instead of repairing them (Maphosa & Maphosa, 2020).

Additionally, manufacturing companies are designing electronic devices and gadgets with shorter lifetimes, making them obsolete quickly and leading to more frequent replacements. This is usually done to inspire consumers to buy new products to generate more profit for the firms. Furthermore, manufacturing makes the design of EEE more difficult or even impossible to repair or refurbish, which directs to discarding devices and the generation of E-waste rather than replacing them (Global E-waste Monitor, 2020).

E-waste creates top and severe issues globally because it involves more than just the amount of waste that is increasing (Ankit et al., 2021). However, a significant amount of solid waste comprises E-waste, which contains precious elements like gold, silver, and copper that can be recycled and used to protect the finite natural resource. Additionally, it contains a number of dangerous substances and heavy metals that, if mishandled, can negatively affect the environment and human health (Purchase et al., 2020). Environmental pollution is possible in several ways. First, in the informal way of managing E-waste, it’s dumped in the landfill; thus, the hazardous chemical composition of EEE, such as “mercury, cadmium, lead, chromium, poly/brominated flame retardants, ozone” leached to the soil. In this way, it pollutes the groundwater and causes emissions to the surface water and surrounding air (Ankit et al., 2021). For instance, one mobile phone battery is estimated to pollute six hundred thousand liters of water (Rajesh et al., 2022). According to other researchers (Li & Achal, 2020; Lin et al., 2022), water pollution due to E-waste

affects seafood, fish, rice, and vegetables. Another method of extracting valuable metals such as gold, copper, and silver in informal waste management is burning E-waste, which releases harmful fume into the air. This contributes to the pollution of the air and the environment.

Proper and standard E-waste management solves the problems mentioned, like protecting the environment, preserving rare resources, and controlling health hazards that arise from E-waste pollution. If E-waste is managed correctly, up to 90 percent of base metal and 97-98 percent of precious metals is recoverable (Huisman, 2003, as cited in Pan et al., 2020).

The mentioned problems due to E-waste attracted the attention of policymakers, researchers, and the government to manage it properly to control waste generation. E-waste and other solid waste collection and recycling are managed appropriately in developed countries such as Germany, Sweden, and Switzerland. This is done through enacted policy, technical employees with knowledge of E-waste management, good infrastructure, and usage of digital technology(Kurniawan et al., 2023). For instance, in developed countries, manufacturers are responsible for managing or taking back the E-waste of their EEE from consumers by enacting a policy called EPR (Wang et al., 2013, as cited in Maphosa & Maphosa, 2020). CE is another approach that lately developed countries have implemented for reducing E-waste generation. To reduce fast disposal and increase the lifetime of EEE. CE suggests the modular design of products in which every component be replaceable easily. Therefore, the consumer can repair the product in case of damage or malfunction instead of disposing of the whole product. Furthermore, the CE concept emphasizes closing the loop and reducing waste through different principles such as reverse logistics, reuse, and recycling of E-waste (Ottoni et al., 2020a). Look at the CE economy section for more details about the principles of CE for reducing E-waste generation.

3.2. Waste Management and Waste Reduction

Various urban development, city clearance, drive toward sustainability and waste reduction require proper waste management (Sepasgozar et al., 2021). Waste management, according to (European Parliament, 2015 as cited in Dils, 2020), is defined as “the discipline

associated with control of generation, storage, collection, transport or transfer, processing and disposal of waste materials in a way that best addresses the range of public health, conservation, economic, aesthetic, engineering, and other environmental considerations. Its scope includes planning, administrative, financial, engineering, and legal functions" (p. 5). Waste prevention is a proactive approach to address issues before substances, materials, or products become waste. It encompasses several strategies, including, the reuse of items to extend their lifespan, the minimization of adverse environmental and human health impacts caused by waste, and the reduction of hazardous components in materials and products. The primary objective of waste prevention is to curtail overall waste generation by implementing measures that promote sustainable resource management and consumption practices. (Directive, E. C., 2008 as cited in Dils, 2020).

3.3. Circular Economy

The linear or traditional business model, which is based on production and consumption, operates based on the assumption of unlimited natural resources. Therefore, the linear business model created significant environmental problems such as climate warming, pollution, and deforestation (Geissdoerfer et al., 2017). Hence, a socio-technical system transition is needed to deal with the linear business model problems. This transition, according to D'Amato et al. (2017), is the CE which is an answer to the concerning threats and problems and is an alternative solution to a traditional linear economy, "make, use, dispose" (D'Amato et al., 2017).

The concept of CE is not entirely new, but recently it has gotten more support and momentum from policymakers, government, researchers, and companies. To be more specific, European countries made a package for CE called European Circular Economy Package (Wuttke, 2018). Also, china implemented the CE law in 2016 (Yuan et al., 2008). Still, researchers have defined CE differently, but the most common and accepted one is: CE is a regenerative or restorative industrial system by design that opposes the open-ended system to face challenges of resource scarcity and minimizes waste disposal (Gregson et al., 2015). For instance, what is considered waste in classic LE should be used as input for another industrial process or as a renewable resource for nature (Hobson, 2016). Similarly, the Ellen MacArthur Foundation introduced the Circular Economy as "an industrial economy that is restorative or regenerative by intention and design" (2013b: 14). In which resource input, waste, emission, and leakage are minimized through different methods such

as durable design, recycling, remanufacturing, reusing, and refurbishment (MacArthur & others, 2013)

In some studies, it's mentioned that CE and sustainability have a weak connection. This is because the economic point is stressed more in CE, where environmental sustainability and social considerations are often neglected (Kirchherr et al., 2017; Miller et al., 2013). However, other researchers explain that alternative strategies, such as cradle-to-cradle and closing the loop, gained popularity when economic analysis showed the benefits of circular resource management. The CE was embraced as an attractive and new sustainable economic principle, as it could coincide with social (minimizing pollution and unhealthy working condition) and environmental (resilience of natural resources) value creation (Van Buren et al., 2016). Even according to Geissdoerfer et al. (2017), CE is viewed as a condition for sustainability because, via CE principles such as reducing waste, reusing material, and recycling, it's possible to achieve sustainability goals while benefiting society and the economy. Therefore, CE and sustainability are closely related.

In the literature, for CE, various gradations or options are mentioned, which are called principles or usually referred to as Rs. This principle ranges from 3Rs to 6Rs (Sihvonen & Ritola, 2015) or even 9Rs (Van Buren et al., 2016). However, according to a study that analyzed the definition of CE, the most commonly referred principle is the 4RS, such as reduce, reuse, recycle, and recover (Kirchherr et al., 2017). Also, this 4Rs principle is proposed by the Waste Directive of the European Union (Directive & others, 2008).

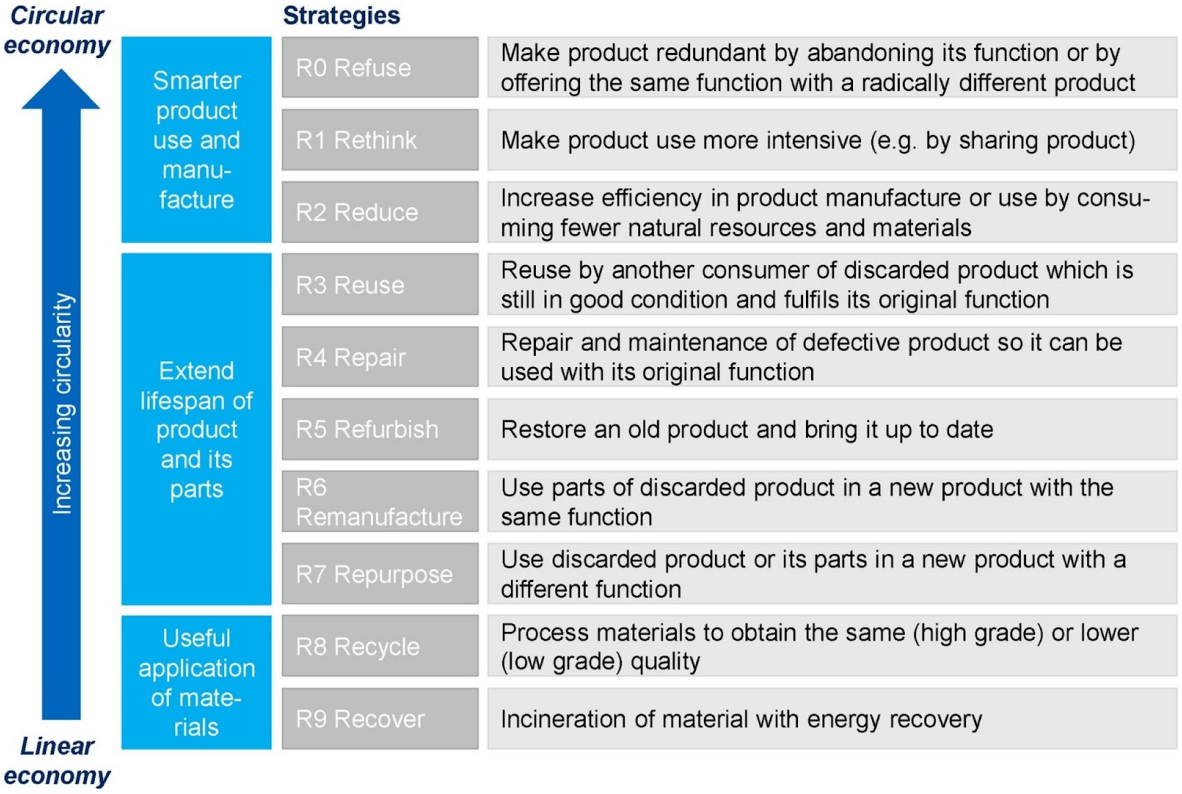

Figure 3.1, 9Rs or CE principles (adopted from (Potting et al., 2017, p. 5))

3.4. Circular Economy for E-waste Management

The transition toward a CE to create value is complex but will result in the emergence of novel business models, value chains, and methods for delivering products and services. This shift will impact the design, production, usage, and disposal processes and the collection of products and materials for reuse (Van Buren et al., 2016). This means that the emergence of novel businesses is required for implementing CE because CE without a business model is directionless and aimless (Kirchherr et al., 2017).

The CE business model can broadly be categorized into two groups. The first one aimed at extending the product lifetime through modular design, reuse, remanufacture, and repair, which is referred to as slowing the loop. The second category involves strategies such as recycling to close the resource loop by utilizing waste as input to manufacture new products (Stahel, 2016). For the implementation of CE, a collaboration between various stakeholders, such as manufacturers, policymakers, consumers, and SMEs, that are innovating and implementing CE is necessary (Antikainen et al., 2018). Similarly, for effective management of E-waste, collaboration between stakeholders is essential.

To illustrate this, manufacturing firms can adopt better slowing the resource loop model of CE while recycler industries can collaborate by closing the loop. To understand better, consider manufacturers are responsible for the cost of disposing of E-waste. Thus, they may design EEE in a modular way that allows the component and parts can be disassembled easily and separated in the cause of obsolescence or damage. In this way, the consumer must deal solely with defective parts and retain the original product. In addition, manufacturers, through modular design, can help recycle industries, and it will solve one of the current E-waste recycling problems (see section 3.1). This is because modular design facilitates the disassembly and soring of E-waste components (Ottoni et al., 2020a). Increasing the lifespan of EEE has both economic and environmental advantages. For example, prolonging the life of household appliances like washing machines, smartphones, laptops, and vacuum cleaners in the European Union by just one year would result in a yearly reduction of approximately four million tonnes of carbon dioxide emissions by 2030. This reduction is comparable to the annual emissions of more than two million cars (Electronic Waste and the Circular Economy - Environmental Audit Committee - House of Commons, n.d.) Moreover, EEE manufacturing companies can collaborate to minimize E-waste through various strategies of CE such as reuse, remanufacture, recycle, servitization, and reverse logistics (Acerbi & Taisch, 2020).

In the consumption phase, consumers can collaborate reducing E-waste generation through various strategies, and this can be merely accomplished by not using unnecessary products if possible, refusing (R0), or other strategies to extend the lifetime of products such as “ones adopted in the production phase: reducing (R1) the overuse, reusing (R2) or reselling while it is still in a good functioning state, or repairing (R3) it if damaged” (Ottoni et al., 2020b, p. 4). However, rising consumer awareness regarding CE and the impact of unsustainable products on the environment is a challenge for the implementation of CE (Islam et al., 2021). However, DTs are considered enablers of CE, especially in informing consumers, changing their behavior, and helping to sort the waste properly.

The Recycling industry's role in controlling E-waste generation in the land field would be through strategies such as reverse logistics and recycling precious and secondary raw materials from E-waste (Ottoni et al., 2020b). In addition, the CE R-based principles are closely related to the waste hierarchy concept. This is because both CE R-principles and waste hierarchy cover all product life cycles: pre-use, use, and post-phase. The idea of the waste hierarchy places waste management solutions in a particular order, from the most

desirable to the least ideal. The hierarchy is frequently depicted as a pyramid, with the most popular alternatives at the top and the least popular ones at the base. The following choices typically fall within the waste hierarchy: Rethink & redesign, reduce, reuse, recycle, and dispose of (Zhang et al., 2022).

In general, E-waste management hase received more attention from CE to minimize waste. The second material is extracted and can be used as input for making new products that save waste and create new value (Trigkas et al., 2020). Specially E-waste in the paradigm of CE should be valued more to preserve rare minerals, control the market price, and not let the environment get polluted with precious minerals of EEE (Global waste monitor, 2020). CE principles implementation will reduce the generation of E-waste significantly. Otherwise, in the linear setting of the business model, it's estimated that the amount of EEE on the market will be doubled by 2050 (UNEP, 2023).

3.5. Digital Technologies Potential for CE

Digital technologies (DTs) include but are not limited to IoT, AI, Big Data, and Data analytics (Liao et al., 2017). DTs have been used by various industries for different purposes, which has heavily transformed our economy already; also, it's a potential role in waste management, and CE is not an exception (Dils, 2020). According to Lopes de Sousa Jabbour et al. (2018), the general characteristic of DTS is enabling connectivity between machines, employees, stakeholders, and consumers to promote accuracy and integrity and optimize the process, mainly in manufacturing companies.

In the context of CE, DTs are mainly considered crucial enablers of CE (Uçar et al., 2020). However, researchers such as (Chauhan et al., 2022; Rosa et al., 2020) believe that DTs cannot solve all CE problems but will foster CE implementation. Numerous research has been done to study the relationship of DTs with CE, see for instance (Bag et al., 2021; Chauhan et al., 2022; Peiró et al., 2021); the results of mentioned studies show that DTs are enablers of CE, however, with numerous challenges and limitation that the firms or organizations need to overcome. As mentioned in the CE section, the business model of CE can be divided broadly into two categories: Slowing and closing the loop (Stahel, 2016). DTs in each CE business model have a crucial role in driving success and advancement. As an illustration, within the context of slowing the resource loop, manufacturing companies can leverage digital technologies to enable real-time monitoring

of products, control the flow of data, collect data from various stages of the product lifecycle, and analyze it for sustainable development, enhanced production processes, resource and waste reduction (Kagermann, 2015). This can be done via IoT and RFID for data collection and transmission, data analytics and AI for analyzing the data and automation, infrastructure, and cloud manufacturing, which connect systems and platforms. In this way, data can be used for better maintenance and extending the lifecycle of a product but also to connect various stakeholders like government, private sectors, and consumers by sharing information and facilitating communication (Kagermann, 2015; Peiró et al., 2021).

To close the loop, DTs can be used to conserve raw materials, reuse secondary products, and reduce waste by keeping the materials and products in the loop or value chain (Viswanathan & Telukdarie, 2022). For example, in reverse logistics, IoT, RFID tags, and AI can keep track of products or materials until their end of life and return them to manufacturing companies to produce new products (Sun et al., 2022). Similarly, recycling industries for waste management can use DTs for better collection, transportation or logistic route, sorting, and disposal to reduce the operation cost and foster the operation (Maiurova et al., 2022). In addition, collaboration between stakeholders and actors is a crucial factor in adopting CE because one company cannot close the loop, but stakeholders can. DTs can facilitate communication between actors, including consumers, through transparency and data sharing by using IoT, e-procurement systems, and AI (Antikainen et al., 2018; Peiró et al., 2021).

DTs are a crucial driver for a transition toward sustainability in waste management and recycling. Because it reduces resource and operation costs while increasing productivity (Borchard et al., 2022). In addition, digital technologies, particularly artificial intelligence (AI), can be utilized to involve consumers in the appropriate segregation of waste actively (mobile applications have already been used to provide information on how to recycle waste based on pictures) and incentivize their active participation through positive reinforcement and recognition for their improved waste separation practices (Modgil et al., 2021). AI not only in waste management but also has been proven efficient in all other sectors, including the economy, as its presence connects billions of IoT through autonomous communication and data analysis (Tavares et al., 2009). Thus, recyclers can considerably reduce their business operation costs and increase productivity through data-driven decision-making, automation of recycling, and separating E-waste. This way,

human hazards also will be reduced, specifically in the E-waste sector (Borchard et al., 2022). According to Kurniawan et al. (2023), DTs are in the maturity phase in some parts of smart waste management, like collection, but smart waste bins are already tested. Real-time monitoring of waste quantity and quality has been made possible through the integration of IoT and RFID, leading to better logistics and transportation (Kurniawan et al., 2023).

Challenges of DTs in the context of the CE, according to Antikainen et al. (2018), in summary, is data related challenges and competency challenges. The stakeholder's contribution is necessary for CE, but big data ownership and sharing could be more problematic and challenging. This is because of privacy concerns and competition among actors and stakeholders. In the competency challenge, actors do not sufficiently understand the value of digital technology and the basic concept of CE. According to Rajput & Singh. (2021), costs associated with implementing digital technology, such as infrastructure, technology maintenance, training employees, and system integration, are a barrier, especially for SMEs with limited financial resources. Another common concern related to digital technology is job replacement and unethical decisions by AI (Tavares et al., 2009).

3.6. Policy Impact on The Transition of CE and Reduction of E-waste

CE attracted the attention of policymakers globally; however, EU countries are at the forefront (Shittu et al., 2021). In the EU, several rules and regulations have been put into place to encourage the adoption of CE practices. These regulations are meant to foster the shift from a linear to a CE, where resources are used more effectively, waste is reduced, and products are made to be long-lasting, reusable, and recyclable (D'Adamo et al., 2022; Rizos & Bryhn, 2022; Shittu et al., 2021). The policies encompass a diverse range of measures concerning multiple aspects, including product design and manufacturing, waste minimization, producer responsibility, and consumer regulations. These policies are strategically designed to attain sustainability goals and protect the environment and human well-being. For instance, the circular economy action plan (CEAP) focuses on preserving natural resources by returning more than consumed based on the "regenerative growth model". Additionally, the CEAP encompasses the entire life cycle of a product, including durable design, waste reduction, repairability, reusability, maintenance, and recycling (Šipka, 2021).

In the domain of waste management, there is a directive called Waste Framework which focuses on the general rule of waste. At the same time, the WEEE 2012/19/EU covers specific E-waste rules. This framework offered extended producer responsibility (EPR), which aims to obligate manufacturers financially to take care of their E-waste instead of municipalities. This policy also incentives producers to design EEE more durable and modular. So the products last longer, and the components will be separable easily for recycling and reuse (Barapatre & Rastogi, 2022). According to (Rizos & Bryhn, 2022, Šipka, 2021), consumer law is well-established in the EU because it includes specific environmental regulations, such as mandated energy efficiency labels and voluntary eco-labels. However, the CE and these policies are unconnected and thus raise the possibility of increased unsustainable usage of EEE. The CEAP makes adjustments to consumer legislation to solve this shortage. The objective is to ensure that customers are given accurate and pertinent information about items, such as their lifespan, and whether repair services, replacement parts, and repair manuals are offered at the point of sale.

The CEAP also recognizes digital technologies as an enabler and facilitator of CE. This is because, with digital technologies, according to Šipka (2021), the issue of data sharing and ownership between stakeholders for the implementation of CE will be addressed by having a common European data space. Also, the sustainable product initiative of CEAP encourages using DTs and systems like digital product passports (DPPs) for tracking products and having updated information for better waste management.

While legislation plays a significant role in driving the transition towards a CE, as discussed previously, it is essential to acknowledge that policy effectiveness limitations pose challenges for firms adopting CE practices. The study conducted by Rizos & Bryhn (2022) highlights various limitations, which include inadequate eco-design requirements to promote circularity, not efficient enforcement of E-waste regulations, lack of legislation for transparent supply chains, not enough international CE standards, and a shortage of incentives for collecting unused devices. Additionally, inconsistent conditions stemming from various policy domains at the European Union (EU) and national levels are barriers. Furthermore, according to Šipka (2021), the inconsistent implementation of the principles outlined in the WEEE Directive among EU member states is an additional concern. Since E-waste is managed by multiple stakeholders (i.e., manufacturers, municipalities, recyclers, and other actors), however, the responsibility of each actor is not specified in the WEEE Directive, which causes confusion. Determining specific actor responsibility would

improve recycling management. Also, a significant issue is insufficient coordination between authorities and relevant stakeholders to effectively address the challenges of accurate reporting and tackling the informal sector in managing E-waste (Cheshmeh et al., 2023; Rizos & Bryhn, 2022). In simple terms, policies and governance processes can be more complicated than they seem. Existing rules and practices may resist policy changes, and people's responses to policies can be diverse and unpredictable. Both policymakers and the public play a role in driving transitions, and the success of a policy depends on how well policymakers understand the existing system and involve various actors in the process (Smith et al., 2010).

The developed countries are mainly the exporter of E-waste, and developing countries are legal and illegal importers of it; this is because of weak policies in developing countries (Srivastava & Pathak, 2020) and complicated and overlapping policy requirements in developed countries like the EU which causing bureaucratic issues (Trigkas et al., 2020). For example, there are obstacles in establishing cross-border markets for used EEE within and outside the EU. This hinders the transportation of equipment to refurbishment or recycling facilities. The issue is exacerbated by the prevalence of illicit shipments of E-waste, which frequently find their way to unauthorized recycling facilities lacking proper health and safety standards (Davide, 2016).

Lastly, it is worth noting that the WEEE Directive does not establish a direct correlation between the management of E-waste and the utilization of data and digital solutions, except for the specific mandates about the responsibility of producers in furnishing information to waste operators. The existence of the I4R Platform serves as an exemplification of information dissemination within this domain. Nonetheless, it is essential to acknowledge that the references made within the Directive regarding the modalities of informing waste operators appear to be somewhat imprecise or outdated (Šipka, 2021).

4. Theoretical Framework

4.1. Sustainability Transition

In recent years, the world has been dealing with significant environmental and sustainability issues in many fields. Fortunately, there have been proposed many solutions to address these challenges. One such solution is CE, which has gained attention as an innovative sustainable business model in various industries (Kirchherr et al., 2017; Uçar et al., 2020). Sustainable transition, on the other hand, is not a linear transition process, but it is a complex transformative process due to several distinct features; the characteristics are the following but not limited to: "*multidimensional and co-evolution nature"*: transition involves simultaneous changes across various dimensions of socio-technical systems, with interdependent developments. *The plurality of actors*: multi actors enact the transition, each playing a distinctive role in the process. *Long-term process:* Transition can take several years to achieve sustainability goals. *Uncertainty*: The multi-pathway of sustainable transition is open-ended, where uncertainty is prevalent. *Values, contestation, disagreement:* The concept of sustainability is subject to intense contestation, leading to differing perspectives and disagreements among actors involved in defining and shaping transition pathways. *Policy and regulation role*: Public policy plays a pivotal and central role in driving and shaping transitions toward sustainability, serving as a critical instrument for creating supportive frameworks and enabling (El Bilali, 2019, 2020).

Sustainable transition offers numerous environmental, social, and economic benefits. However, achieving sustainable goals faces several challenges that hinder its progress. Strong path dependence and lock-in mechanisms, such as sunk investment and economies of scale of existing socio-technical regimes, are one of the challenges. These regimes tend to maintain the status quo, hindering the adoption of more sustainable alternatives (Safarzyńska & Van Den Bergh, 2010). Because established regimes are deeply intertwined with the current technologies, user behaviors, societal norms, economic models, supply chains, organizational setups, and even political and regulation frameworks (Rip et al., 1998; Smith, 2007). Therefore, incremental innovation is more prevalent than radical innovations in established social-technical systems (Dosi, 1982; Frantzeskaki & Loorbach, 2010). However, such incremental changes alone may not be adequate to address the prevailing sustainable issues.

Another significant obstacle niche or innovative firms face is the expensive cost of sustainable solutions. These solutions often require significant investment and come with higher costs compared to traditional alternatives. This financial hurdle may prevent the adoption of such solutions, especially for companies, businesses, or governments with limited resources. (Radinger-Peer et al., 2021). Furthermore, as Geels (2011) states, companies are still confused about generating profits by addressing unstainable issues. This challenge is largely due to the uncertainties that come with implementing innovative and sustainable business models.

Additionally, people or customers often resist paying higher costs for sustainable products compared to cheaper, non-sustainable alternatives. This stems from a lack of accustomedness to paying for low-carbon or environmentally friendly goods and services, mainly stemming from a lack of information and awareness regarding sustainability (F. W. Geels, 2002). Overcoming societal inertia and promoting sustainable attitudes and behaviors are crucial for a successful transition. However, changing societal attitudes and behaviors is a complex task that requires raising awareness, educating, and transforming social norms. These efforts are essential to foster a shift towards sustainable lifestyles and consumption patterns (Islam et al., 2021; Wieser & Tröger, 2018). Also, policy impact significantly on the sustainability transition. The transition is influenced by political framework, policy, and regulatory measures. However, conflicting interests, lack of coordination, and short-term political considerations can create hurdles in implementing effective policies and impede progress toward sustainability (Lauridsen & Jørgensen, 2010).

Technological innovation and research play a pivotal role in sustainable transition. Advancing sustainable technologies and scaling up their deployment are crucial steps. However, achieving technological readiness and overcoming technological barriers require substantial research, development, and innovation investments. These efforts are essential to widely adopt sustainable technologies (Kemp et al., 1998). To sum up, according to Markard et al. (2012), a sustainable transition is a multidimensional, complex, and interconnectedness transformation process that transforms socio-technical systems to more sustainable production and consumption over a long period. Sustainable transition or the momentum of socio-technical systems to overcome the challenges demand policy (Smith et al., 2010).

4.2. MLP Framework Overview

This study investigates the role of DTs in enabling CE and what key non-technological factors impact the transition towards a CE using the multi-level perspective (MLP) framework as a lens. Persistent problems such as climate change, waste disposal, and resource depletion due to LE require a shift toward a sustainability transition like CE. According to (Markard et al., 2012), the sustainable transition is a multidimensional and fundamental transition in which multi actors (individuals, firms, entrepreneurs) and institutions (norms, regulations, good practice, and standards), as well as knowledge, works together in a coordinated way to shift in a more sustainable mode of production and consumption. Thus, in this research, MLP is an appropriate theoretical foundation because it offers a comprehensive framework to explore complex and multi-level interactions of three analytical levels such as niches (micro level), soci technical regimes (Meso level), and landscape (macro level) levels, by considering not only technological but also societal and institutional value and dimensions to analyze and understand sustainable transition (F. W. Geels, 2018; Schot & Geels, 2008). The socio-technical regimes account for the stability of the existing system by practicing current routines, norms, rules, and regulations; while niches serve as a protective environment for radical innovation; and the landscape contains external factors which affect changes in both niches and socio-technical regimes (Geels, 2011; see also, Rip et al., 1998).

The history of MLP can be traced back to multiple researchers; first, MLP was declared by Rip and Kemp (Rip et al., 1998) but later developed further by (F. W. Geels, 2002). The MLP framework was developed based on insights from different studies, combining knowledge from evolutionary economics (concerning technological development paths, dominant systems, and emerging alternatives), the sociology of technology (highlighting the social construction of innovations through interactions among engineers, companies, consumers, and policymakers), and neo-institutional theory (focusing on how actors are influenced by shared beliefs, norms, and regulations) (F. W. Geels, 2012). According to F. W. Geels (2004), “Social sciences, evolutionary economics, business studies, and innovation studies” see the production and usage of products as two separate clusters by focusing more on the production and innovation part than the user side. In contrast, cultural and domestication studies focus more on the user/consumption side by highlighting that

not only artifact learning and usage is essential but also the cultural appropriation of technologies is part of usage (see, e.g., Du Gay et al., 2013; Van Dijck, 1998). However, MLP, unlike the mentioned studies, focuses on multi-analytical layers and analyzing their multi-dimension interaction rather than only on the technological or behavioral side (F. W. Geels, 2004). This holistic perspective is well-suited for studying complex, uncertain processes such as sustainable transitions. By examining the interplay between different analytical layers, the MLP offers valuable insights into the dynamics of socio-technical systems in transition (Markard et al., 2012).

The MLP examines transitions or systemic changes as socio-technical transition systems encompassing various components, namely niche, socio-technical regime, and landscape, to fulfill societal functions. The strength of socio-technical systems lies in their ability to view the process as multidimensional and coevolutionary, considering the interplay between technology and society rather than a linear progression. These systems encompass not only sectors and industries, which is the conventional economic perspective, but also encompass usage, cultural aspects, and political implications. For instance, in the context of the car system, the functioning of a car relies on factors such as infrastructure and a market, and ultimately, the user incorporates it into their lifestyle (F. W. Geels, 2004).

To explain in detail, MLP has the following characteristics; first, co-evolutionary and systemic approach: the transition from MLP lenses is not solely influenced by a single factor, such as technological advancements or price changes. Rather, it is driven by the co-evolutionary growth of various dimensions, including technology, industry, markets, consumer behavior, policy, infrastructure, spatial arrangements, and cultural meaning. Second, the Actor-based approach: the MLP concentrates on the processes, perceptions, activities, and interactions of actors such as car drivers, transport planners, car manufacturing firms, and public opinion. It recognizes the significance of their roles in shaping transitions. Third, stability and change: The MLP recognizes the presence of stability, resistance to change, and lock-in, while also acknowledging the possibility of radical and systemic change. It acknowledges that established systems can coexist with emerging innovative and transformative elements (F. W. Geels, 2004, 2012). Fourth, complex dynamics: The MLP places less emphasis on linear cause-and-effect relationships or simplistic drivers of change. Instead, it focuses on the interaction of mutually reinforcing developments, alignments, co-evolutionary processes, innovation cascades,

knock-on effects, and cycles of enthusiasm and disappointment (Smith et al., 2010). To sum it up, the MLP has a thorough and adaptable method for comprehending transitions. It considers various factors, the impact of different actors, the co-occurrence of stability and transformation, and the complex dynamics that shape socio-technical systems (F. W. Geels, 2012, 2018; Markard et al., 2012).

Researchers (Schot & Geels, 2008) recommended MLP as a theory for studying such transition. Because MLP addresses the multi-dimensional nature of sustainability transition and dynamic structural change. In the MLP, the basic permission is that transition is a non-linear process. This transition results from an interaction between three analytical levels: niches (the locus for radical innovations), socio-technical regimes (the locus of established practices and associated rules), and an exogenous socio-technical landscape (F. W. Geels, 2018; Rip et al., 1998). Three analytical levels of MLP are explained in the following.

4.2.1. Socio-technical Landscape

The socio-technical landscape is a larger context that forms the external structure or framework for interacting with actors. “It is a landscape in the literal sense, something around us that we can travel through; and in a metaphorical sense, something that we are part of, that sustains us” (Rip and Kemp, 1998, p. 334). According to Geels. (2002), the socio-technical landscape refers to external factors, such as war, migration, and environmental issues, that affect both the niche and the regime. Landscape factors can pressure established regimes and create favorable conditions for niches to emerge and drive significant changes or shifts within socio-technical regimes. In addition, Rip et al. (1998), states that individual actors have no control over the socio-technical landscape. Also, changes in the landscape are slow.

4.2.2. Socio-technical Regime

The socio-technical regime is a central concept representing established systems with lock-in and path-dependent mechanisms via a dominant set of rules, norms, practices, and technologies that shape a specific sector or industry. This stability is derived from the socio-technical configuration, which results from various actors' linkage, interaction, and

activities and having a deep structure. The stability is dynamic, which means that innovation still occurs not radical but in an incremental way because of the regime's stability (F. W. Geels, 2002; Smith et al., 2010). However, the regime's stability creates a lock-in, which explains why innovations are challenging to affect or alter the regime. (Kemp, 1994). This concept (socio-technical regime) is developed based on the technical regime, which was first proposed by evolutionary economists Nelson & Winter (1977). Technical regime represents the dominant beliefs and practical designs that impact innovators within companies. These beliefs steer innovators towards pursuing options that appear marketable or feasible while disregarding less attractive alternatives. This notion shares similarities with Dosi's (1982) research on technological trajectories and paradigms. Later, Rip and Kemp (1998) expanded the scope of the technical regime concept by associating it with the sociological concept of 'rules'. Lastly, to refer to the semi-coherent set of rules carried by different social groups Geels (2002) used the term 'social-technical regime'.

4.2.3. Niche

Niche is another essential concept in the transition process, as it involves both technological and non-technological innovations. A niche is conceptualized as a specific area where new and innovative ideas can develop and potentially disrupt the current market. These niches tend to be slow-moving and protected from the mainstream market (Kemp et al., 1998). The researcher believes that niche development is vital for a transition to a sustainable one. (F. W. Geels, 2018). This niche development, according to (Kemp et al., 1998), is divided into three processes:

- Learning processes on various dimensions, e.g., technological flaws and how to fix them, organizational problems, market demand, user behavior, infrastructural needs, policy tools, and symbolic meanings.
- The expression (and modification) of goals or ideals that direct innovation activities and seek to gain support and funding from outside parties.
- The development of social networks and the inclusion of more participants increase the available resources for niche breakthroughs.

Niches gain momentum when expectations are more specific and widely accepted when different learning processes align to create a stable configuration (known as a "dominant design"), and when networks grow (especially when powerful actors participate, which can

lend legitimacy and resources to niche innovations) (F. W. Geels, 2018). The outcomes of these interactions between niches, regimes, and the broader landscape are contingent upon the timing and the qualitative nature of their interactions. All three layers - landscape, niche, and regime - interact when transitioning. This interaction is known as a multi-level perspective (Geels, 2002).

Figure 4.1 shows the dynamic interaction of three analytical levels in a socio-technical transition. Despite the fact that every transition is different, the overall dynamic pattern is characterized by transitions that come about as a result of interactions between processes at various levels: (a) niche innovations generate internal momentum, (b) changes to the landscape put pressure on the regime, and (c) destabilization of the regime opens doors for niche innovations. The MLP eliminates straightforward causality in transitions, which is a significant implication. There isn't just one "cause" or "driver." Instead, there are processes in several dimensions and at various levels that connect to and reinforce one another (known as "circular causality") (F. W. Geels, 2011)

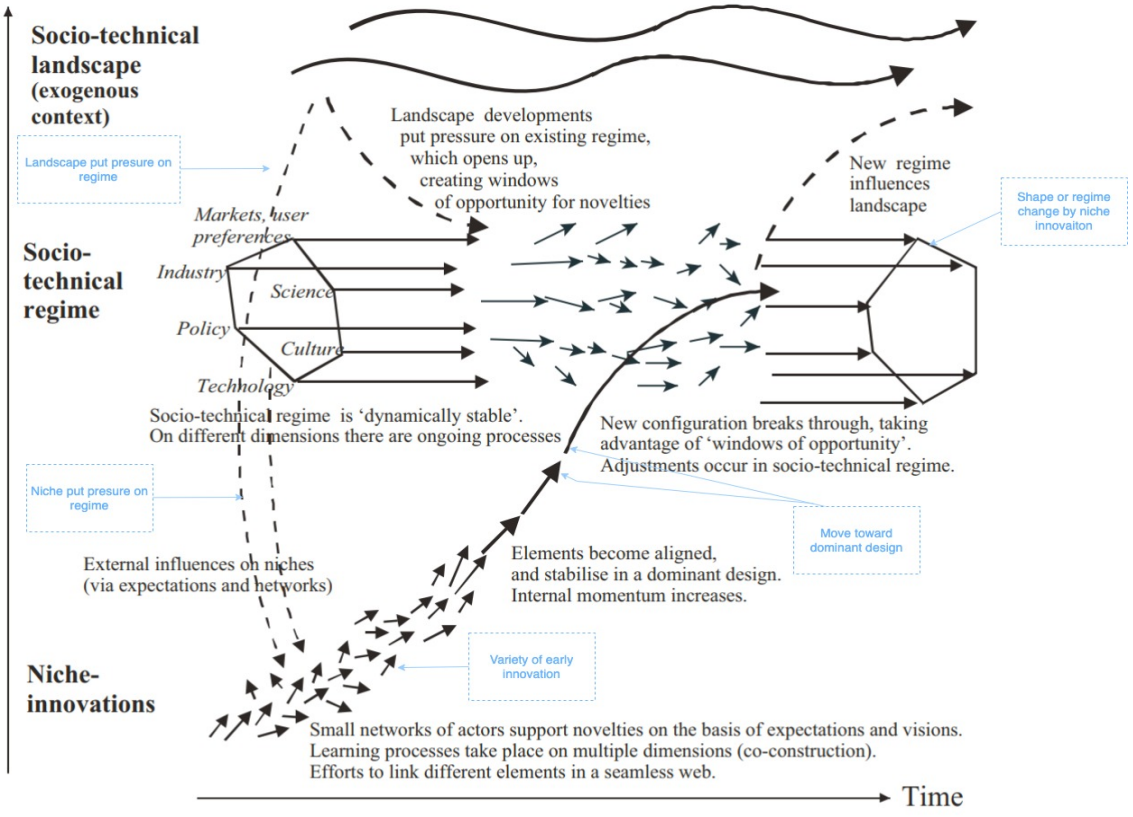

Figure 4.1, Multi-level perspective on transition (adopted from (F. W. Geels, 2002, p. 1263))

Transitioning toward CE from LE creates different relations between critical partners and stakeholders and creates new activities and new value propositions for customers, industry, and the environment (Bocken et al., 2016; Reim et al., 2021). This transition is sustainable. Since various other researchers have used MLP to study sustainable transition; see, for example, in electricity (van Bree et al., 2010) and mobility and green cars (R. P. J. M. Raven, 2004). Therefore, MLP could be an excellent framework for studying the problems mentioned earlier in this paper.

4.3. The MLP's Allure for Sustainability

Sustainable development requires a broader perspective in two dimensions. First, "broadening the problem framing". In the past, innovation was mainly focused on solving specific problems; however, now, there is a broader understanding that innovation should go beyond developing individual technologies and focus on the entire system. The second one is "broadening of the analytical framing" The concept of sustainable development emphasizes the significance of innovation's normative direction. This new direction means that there is an increasing acknowledgment of the importance of considering the social, technological, and institutional factors of innovation beyond just its economic potential (changes in prices). Long-term sustainable innovations can significantly affect society and the environment, and it is crucial to consider this (Smith et al., 2010).

In such a setting, MLP has been believed to be a good framework for analyzing a multidimensional transformation toward sustainability (F. W. Geels, 2002, 2004, 2018). However, many theoretical frameworks have been developed for analyzing and conceptualizing the transition toward sustainability (El Bilali, 2020; Markard et al., 2012). Some examples of relevant theories include but are not limited to, sociotechnical transition, actor-network theory, and social practice theory (Callon, 1999; Lawhon & Murphy, 2012). The most common and central ones, according to (El Bilali, 2020; Markard et al., 2012), are multi-level perspectives on socio-technical transition, transition management, strategic niche management, and technological innovation systems, which I will explain in detail below (see for example figure 4.2).

Transition Management, according to Markard et al. (2012), combine concept from technological transition and complex system theory (Kauffman, 1995) and governance studies (Rotmans et al., 2001). Transition management is a comprehensive and multi-level

framework that influences the co-evolution of societies to create a sustainable future. It includes having a clear vision of what we want to achieve, trying out new ideas through experiments, and being open to learning and adapting along the way (Loorbach & Rotmans, 2010). Transition management also focuses on influencing and coordinating the actions and behaviors of various actors involved so that they can work together effectively and compete with the established practices and actors in mainstream society (Kemp et al., 2007).

Strategic niche management (SNM) is another vital concept in transition studies. It provides a safe environment for innovation where technologies are introduced and adopted through social learning and experience (Kemp et al., 1998). New and sustainable solutions can gain momentum in specific industries, ultimately replacing existing technology or practices. Supportive policies can facilitate this transition. (Schot & Geels, 2008; Sushandoyo & Magnusson, 2014). In niche management, not only the technological change but also the connection between technology and social transition is considered (Schot & Geels, 2008).

In recent years, a multi-level perspective (MLP) developed based on transition studies and ideas of Kemp, Rip, and Schot (Kemp et al., 2001; Rip et al., 1998). MLP is a non-linear process that explains technological and non-technological transition by the interplay of three dynamic analytical levels: niches (radical innovations which change or replace the existing technological regime or practice), regimes (existing practice, norms or relevant regulations that stabilize current systems) and landscape (external factors which put pressure on the regime and open window of opportunities for the regime) (for more see the building blocks of MLP framework) (F. W. Geels, 2002).

The technological innovation system (TIS) is the fourth model for transition studies. It focuses on the emergence of innovative technologies and the associated institutional and organizational changes required to support their development. In other words, TIS represents a dynamic socio-technical system where actors and their networks interact and are guided by formal and informal institutions (Kanda et al., 2019). The concept of TIS originated from the influential work of Carlsson & Stankiewicz (1991), who emphasized the systemic interplay between firms and other actors within a specific institutional infrastructure as the key driver behind technological innovations' creation, diffusion, and adoption.

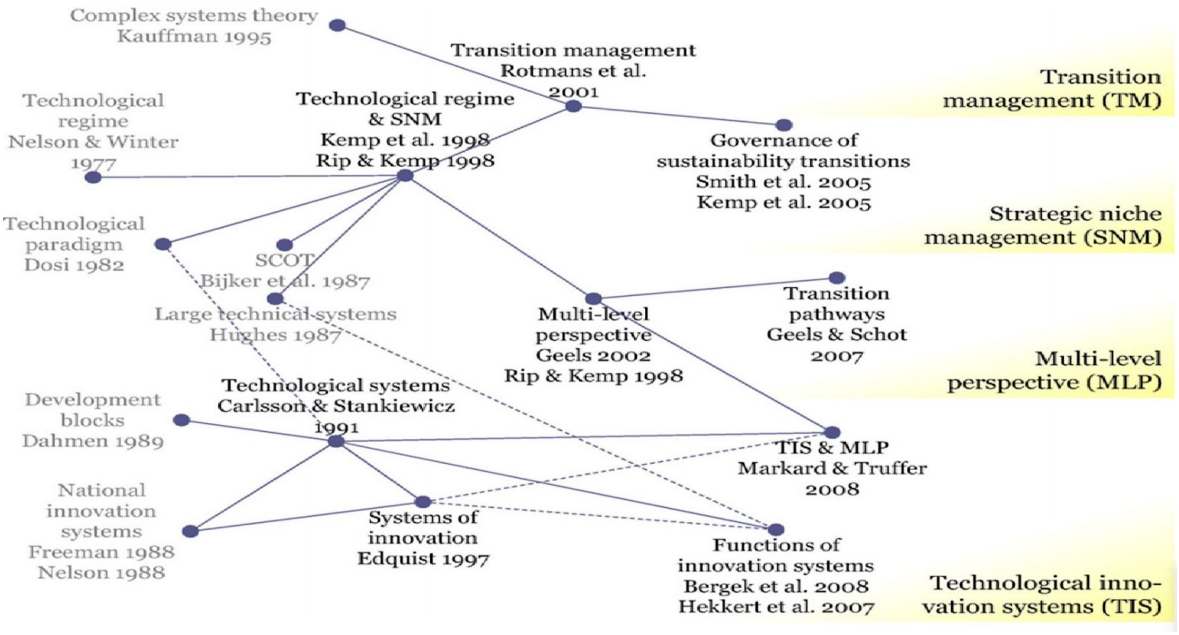

Figure 4.2. Key models for the sustainability transition studies (adopted from (Markard et al., 2012))

In this study, MLP is the preferred theoretical framework for studying the transition of E-waste management toward CE and the role of digital technologies in this transition. MLP, among the mentioned models, recently getting more popular and is increasingly used to analyze and understand sustainability transition and innovation in various domains. For instance, in climate change (Bows-Larkin et al., 2007), sustainable energy transition (Nye et al., 2010), waste management (Lauridsen & Jørgensen, 2010), food and agriculture (El Bilali, 2019, 2020) and sustainable mobility (Nykvist & Whitmarsh, 2008, 2008). Also, MLP has been applied to study the transition path of CE and related circular methods, such as SMEs' transition toward CE practices (Zhu et al., 2022) and the transition of metal management toward CE (Jackson et al., 2014).

MLP is appealing because it simplifies to study of complex and multidimensional sustainable transition by providing a simple and systematic way of analyzing how things are produced and consumed. MLP simplifies the socio-technical system by categorizing three analytical levels: niche, regime, and landscape, which allow researchers to conceptualize the dynamic interaction between actors and understand how innovative changes happening in niches will impact the more prominent aspect of the regime. Therefore, simplification makes complex transitions more manageable (Schot & Geels, 2008). However, Smit et al. (2010) point out that it is essential to be careful in oversimplification to avoid missing the details and have an abstract result.

Another attraction of the MLP is its focus on the role of niche innovations in driving system-level change (Kemp et al., 1998). The MLP suggests that introducing novel concepts and ideas can serve as a catalyst for promoting exploration and education, which in turn can lead to significant systemic transformations. Such transformations are essential for affecting the social, political, and economic changes necessary to facilitate a transition toward sustainability (Schot & Geels, 2008).

Finally, The MLP framework has proven to be a valuable tool in the realm of sustainable development, offering practical guidance on how to analyze sustainable transition. Its applicability in the spheres of policy and governance has been widely recognized, with numerous countries leveraging it to establish well-defined sustainability strategies and goals (Lauridsen & Jørgensen, 2010). This is because the MLP emphasizes that change is needed at multiple levels, from niche innovations to large-scale system change, and requires multi-stakeholder collaboration. By recognizing the importance of collaboration among diverse groups, from policymakers to grassroots organizations, the MLP provides a roadmap for navigating the complex task of achieving a sustainable transition (Nykvist & Whitmarsh, 2008; Smith et al., 2010).

In conclusion, the allure of the MLP in sustainable transition is two-fold: its comprehensive analytical framework and its practical guidance for promoting change. By recognizing the importance of multi-level analysis, niche innovations, and collaborative governance, the MLP offers a powerful tool for researchers and policymakers to address the complex challenges associated with achieving sustainable development.

4.4. Criticism of the MLP

MLP attracted the attention of researchers in the sustainability domain to analyze and study transition. However, it's not free from detectors, and numerous critiques exist regarding the MLP framework (e.g., Geels, 2011; Geels & Schot, 2007; Jørgensen, 2012). In this section, selective criticism, such as the underplaying role of agency and lack of operationalization of regimes empirically, more stress or bias on a bottom-up approach, methodology, or unsystematic usage of MLP and explanatory style, will be discussed.

To explain the criticism in detail, researchers have criticized MLP for not considering the agency's role in the transition. Smith et al. (2005) state that in the socio-technical

transition, more focus on the role and power of norms and politics is necessary, which is lacking in the MLP. In contrast, Geels (2011) argues that lack of agency is incorrect because MLP combines the idea of materialistic (evolutionary economic theory) and ideological (socio-technical system theory) theory. Therefore, the agency exists in the MLP analysis, and its role is considered in transition. However, some agency roles developed less in the MLP, which can be developed further by including insights from social, power, and cultural dimensions. Another critique of the MLP is the 'operationalization and specification of the regime'. Various researchers raised concerns regarding the operationalizations of the regime; for instance, Elzen et al. (2004) contend that "it is unclear how these conceptual levels should be applied empirically" (p.54).

Also, Markard & Truffer (2008) argues that the conceptual differentiation between system and regime is vague because the terms 'system' and 'regime' are used interchangeably to refer to the regime. Therefore, a clear definition and identification of the regime is required. Geels (2011) agrees with this critique and suggests that analysts should specify the boundaries of the regime first and then operationalize the MLP. For distinction of 'system' and 'regime,' Geels says that:

> The system refers to tangible and measurable elements (such as artefacts, market shares, infrastructure, regulations, consumption patterns, and public opinion), whereas regimes refer to intangible and underlying deep structures (such as engineering beliefs, heuristics, rules of thumb, routines, standardized ways of doing things, policy paradigms, visions, promises, social expectations and norms) (Geels, 2011, p.8).

Bias toward the bottom-up model is another criticism that MLP has received. According to (Berkhout et al., 2004 as cited in Geels, 2011) in this approach, MLP focuses more on the niches rather than regime and landscape. However, it is argued that transitions are influenced not only by niches but also by factors at other levels, such as the regime and landscape, which is overlooked in the bottom-up approach. Primarily, this bias is related to the niche management approach, which assumes that transition could be brought about by nurturing niche innovation (R. Raven, 2005). To overcome the bottom-up niche bias, Geels & Schot (2007) propose a typology of four transition pathways and suggest that analyst needs to pay more attention to the regime and landscape level process as well. The four transition pathways clarify the dynamic interaction of niche and regime and provide a

nuanced understanding of strategies or mechanisms of transition. The four transition pathways are *transformation* (in this pathway, the niche cannot break through because they are not developed enough but gets adopted by the regime due to the pressure of landscape, which leads to the adjustment of the incumbent regime), *reconfiguration* (when a new regime grows out of the old regime, where niche are developed enough. In this pathway, regime actors do not die but adapt to the changes to solve local problems. Fundamental structural changes happen, e.g., the transition from regular to LED lights bulb), and *technological substitution* (niches are developed enough which break through and replace the regime due to landscape pressure; however, sometimes, because of internal niche momentum, it replaces the regime without landscape pressure. E.g., the transition from landline phones to mobile phones) and lastly, *de-alignment and re-alignmen*t (landscape pressure creates de-alignment, and innovations use the opportunity and co-exist, which leads to a new regime).

MLP has been used unsystematically. In other words, whether the MLP applied entirely or partially is unclear. In terms of rule and regime, it is not differentiated clearly or apparent which part is easy to operationalize. Thus, greater clarity is necessary for using multi-level models of socio-technical transition (Genus & Coles, 2008). Another concern is that the distinction between radical and incremental innovation is not evident. This is because a stable regime exhibits slow and incremental changes, which will become radical innovations in the long run. However, according to Kemp et al. (1998), differentiation between radical and incremental innovation is challenging if radical changes are also associated with incremental changes.

Finally, another criticism is the ambiguity of how to use the conceptual level of MLP empirically. First, the distinction of niches is challenging since it is embedded in niche-to-niche configuration or to sectors and broader system level. Therefore, clear criteria and boundaries for defining niches and determining their relationships are required in practice, which is challenging (Genus & Coles, 2008). Also, the socio-technical regime could be defined at various empirical levels. For instance, " In the electricity domain, one could study a regime at the level of primary fuel (coal, oil, gas) or the level of the entire system (production, distribution, and consumption of electricity). What looks like a regime shift at one level may be viewed merely as an incremental change in inputs for a wider regime at another level" (F. W. Geels & Schot, 2007, p. 402). Response for the primary one, the role of less stability and stability draw a boundary between niche and regime. For

the latter one, analysts and researchers should pay greater attention to the broader aspects and factors like cultural, political, social, and socio-economical, which impact innovation and its diffusion within sectors and its potential for the systematic transition (F. W. Geels, 2011).

Despite the critiques that MLP hase received, it hase been used widely for sustainable transition, and it is a valuable framework to study multi-dimensional transition (for more, see, The MLP's allure for sustainability).

5. Methodology

5.1. Research Aim and Objective

This research aims to analyze the role of digital technologies (Big data, IoT, AI, applications, and digital platforms) and key non-technological factors that impact transforming E-waste management toward a CE (socio-technical transition). MLP has been used as a theoretical framework for this study to investigate not only technological factors but other factors, such as (political, societal, and economic) that impact transition (F. W. Geels, 2002). The socio-economic linear model is based on "take-make-dispose"; it created significant environmental issues such as global warming, climate change, and waste generation (Geissdoerfer et al., 2017). Production of EEE is not an exception, and it's primarily based on LE economic model. Therefore, E-waste is increasing each day immensely, and it's among the fastest-growing types of waste because of the enormous usage of technical gadgets in our daily life (Ghulam & Abushammala, 2023). Driving toward sustainability and minimizing waste requires proper waste management and implementation of CE (Sepasgozar et al., 2021). DTs are considered an enabler of CE by various researchers (Bag et al., 2021; Chauhan et al., 2022; Peiró et al., 2021). However, there are some uncertainties among other researchers about the role of DTs as enablers of CE (Chauhan et al., 2022; Rosa et al., 2020). Moreover, to the best of my knowledge, no other papers similar to this research have used the MLP framework to study the transition toward CE in the E-waste management context. On the other hand, the transition towards CE in E-waste management is multidimensional; various factors, such as (political, societal, and economic) are involved and impact the transition. Therefore, this research aims to use MLP to explore how digital technologies and key non-technological factors impact the transition of CE in E-waste management.

This study focuses on selecting niche and regime actors in European countries and including one company from the UK. Several reasons underpin the base of these reasons. First, European countries are at the forefront of sustainability and CE. Still, information systems and digital solutions are lacking, so the researcher recommends adopting DTs for efficient CE implementation (Barapatre & Rastogi, 2022). Lastly, applying MLP as a theoretical framework to analyze data of actors from different counties is not limited; however, it's recommended to specify the boundaries of niches, regimes, and landscape,

which this study makes clear in the operationalizing of the MLP section (see, e.g., Nykvist & Whitmarsh, 2008).

5.2. Literature Search

The author of this paper conducted a literature search to understand the problems, and current status of research, understand the gap in the literature, and formulate the research questions better (Bryman, 2016b). Therefore, the literature review was conducted systematically and in several steps.

First, to understand the problems of Electronic waste, the potential of CE, and the role of digital technologies for CE. The author of this paper did a newspaper and website content analysis. For instance, MacArthur's website "https://www.macfound.org/", the WEE forum "https://weee-forum.org/", and the website of big tech companies like ISB Global "https://www.isb-global.com/" were used as a source to gain basic knowledge about the topic. Later, I looked into literature by the following keywords: *E-waste, digital transformation in E-waste, waste management, digitalized waste management, circular economy in waste management, the role of digital technology in waste management, digital technologies and circular economy, role of digital technology in circular economy, multi-level perspective, multi-level perspective and circular economy, multi-level perspective and sustainability.*

The papers collected according to mentioned keywords were categorized into three different groups. The initial set of literature contributes to the knowledge of this paper's author about the concept of CE and the role of DTs within this context. Mainly, it's acknowledged that DTs have the potential to enable CE. However, research pointed out the importance of empirical research to enhance comprehension and provide more evidence regarding the practical implications and outcomes of DTs in CE implementation (Khan et al., 2022). To have a concrete understanding, narrowing of the topic was necessary. Thus, I selected the E-waste management industry because E-waste is rapidly increasing and is among the fastest-growing types of waste globally (*E-Waste Vol. 1: Inventory Assessment Manual*, n.d.). The second category of literature adds knowledge about the problems of E-waste and the digitalization status of waste management. Through this process, the author of this paper developed a solid background in E-waste problems, the potential of

CE, and the role of digital technologies in enabling CE to test during the interviews. See the interview questions in the Appendix 1 for more information.

Second, at the beginning of this study, I selected innovation theories as my theoretical background. Still, after a thorough literature review and professor feedback, I realized that transitioning from a linear economy to CE is a multi-dimensional process. Hence, the MLP framework emerged as a suitable theoretical framework for analyzing sustainable transitions and their multi-dimensional nature. An extensive literature review was conducted to develop a solid understanding of MLP, including its allure and critiques. To be more specific, I have developed an understanding of key concepts of MLP, such as niches (innovation practice), regime (stabilized socio-technical systems), and landscape and how the interaction between these analytical level result in transition. Also, I understand MLP critiques and limitations, ensuring that these perspectives are considered critically in this research. Reviewing the literature about MLP sparked my understanding to formulate my research questions better "not to just focus on technological factors but also on political, societal and economical aspects that impact transition toward CE in E-waste management"

In summary, the literature was systematically conducted using RemNote software. The process involved assigning themes and codes to the information extracted from the papers to facilitate the contextual understanding of the topic. Also, by conducting the literature review, the author developed factual information about the research gap, the problem of E-waste, potential of CE and DTs. This, in turn, guided the formulation of research questions to be addressed in this research.

5.3. Operationalization of MLP Framework

According to Geels (2011), to address critiques regarding the ambiguity of regime and socio-technical boundaries raised by Elzen et al. (2004), researchers should first specify the system boundaries and then proceed with operationalization. In the context of this study, it becomes crucial to consider this advice and establish clear boundaries that delimit the scope of the investigation. By doing so, the research can maintain a focused and specific approach to exploring the potential of DTs in facilitating a CE within the context of E-waste management. Additionally, this approach allows for examining how the interactions among different actors contribute to shaping the transition toward a CE.

In the MLP framework, three dimensions shape the transition: social-technical system, rule and institution, and human actors or social groups. See, for instance, figure 5.1. This study considers these three dimensions, but the main focus is the social-technical system, which will be discussed in the following.

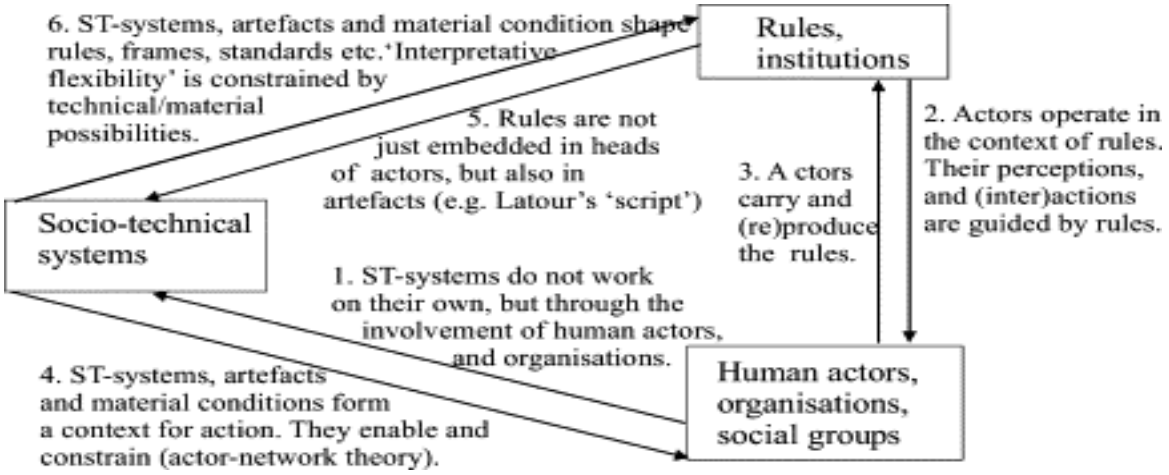

Figure 5.1, Three interrelated analytic dimensions (adopted from (F. W. Geels, 2004))

5.3.1. Socio-technical systems

Socio-technical systems do not operate in isolation; they involve the active participation of diverse social groups and interconnected human actors. These socio-technical systems encompass the entire lifecycle of technology, including its production, dissemination, and utilization, to fulfill society's functional needs. While firms and industries play a crucial role within these systems, it is essential to recognize the involvement of other significant groups, such as users, societal groups, public authorities, and research institutes, as illustrated in Figure 5.1 (F. W. Geels, 2004). In the socio-technical system of waste management, various actors are involved. These actors are producers of EEE, waste processors, waste pickers, institutions, municipalities, policymakers, and technological solutions providers. This study mainly gathers primary data from digital solution providers, organizations that monitor and help producers comply with regulations or achieve sustainability, public authorities from municipalities and waste associations, and sustainability consultants. However, data from producers of EEE and the wider society was not procured. Nevertheless, the research accounts for the factors in the interviews with the actors mentioned above.

This research study investigates the niche and regime dimensions, which entails the policies, rules, and business practices that shape the prevailing socio-technical system. By considering both dimensions, the study aims to avoid overlooking crucial factors that influence transitions. Consequently, the bias towards a bottom-up approach is taken into account. To comprehensively understand the role of digital technologies and their interaction with technical transitions, the research draws upon the transition path typology proposed by Geels and Schot (2007).

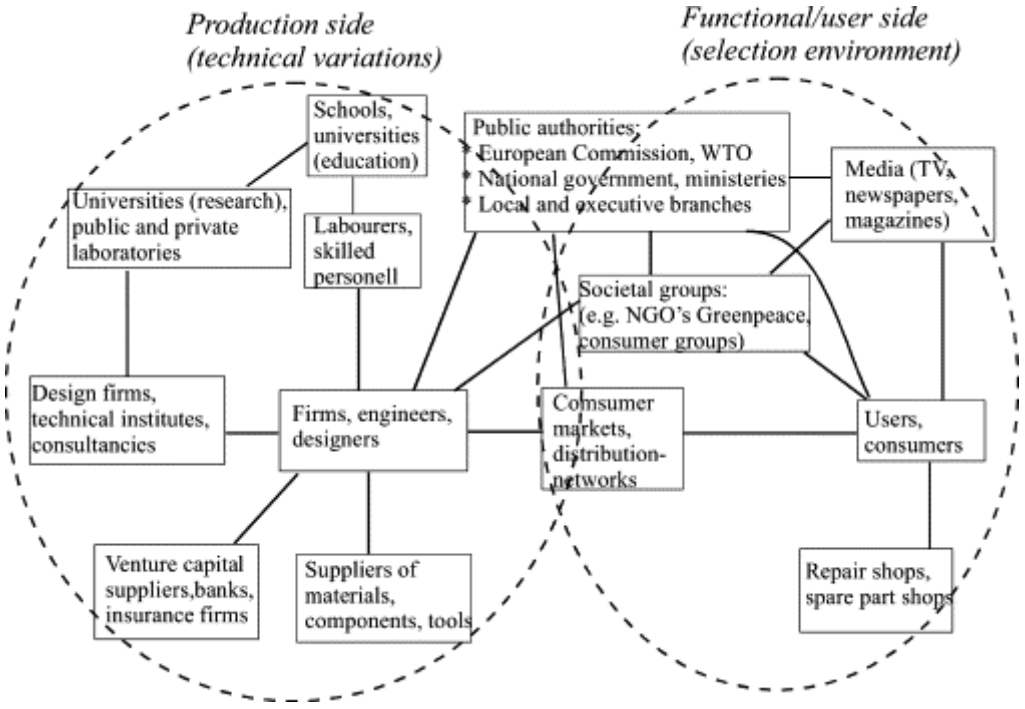

Figure 5.2 Social groups which carry and reproduce ST-system (adopted from (F. W. Geels, 2004)).

5.3.2. Landscape

Landscape represents external factors that put pressure on the regime. Changes in landscape put pressure on the regime and open the window of opportunity for the niche or change the niche trajectory direction. Changes can be slow (economic changes, cultural and demographic, and climate changes), and it can be sharp and radical (war, economic crises, extreme flood or drought) (F. Geels, 2005). This study considers various factors influencing the regime, including climate changes, societal awareness and attitudes towards sustainability and CE, and government policies and regulations that exert pressure on the existing system (regime).

5.3.3. Regime

The regime refers to the established roles, practices, knowledge, and corporate cultures within an institution's infrastructure. It represents a socio-technical system's stable and underlying structure (Geels, 2011). In the context of this research, the regime can be understood as the current set of roles, norms, practices, and stakeholders involved in E-waste management, such as government bodies, waste management companies, producer responsibility implementors, recycling facilities, and regulatory agencies. It encompasses the existing infrastructure, processes, and E-waste technologies for E-waste management.

5.3.4. Niche

Niches are actors who operate in protective or specialized spaces within broader regimes. Novelties in a niche are not only technological but also refer to new policies, practices, or creatively using existing technologies (Geels, 2012, 2018; Nykvist & Whitmarsh, 2008). In the context of this study, it refers to the firms developing technological solutions for E-waste management, sustainability consultants, and collection schemes helping producers to comply with EPR. These actors are involved in new practices or eager to explore new business models, methods, or technology to improve recycling or circularity of E-waste.

5.4. Research Design

This study explores the role of digital technologies in enabling a CE in E-waste management and the impact of key non-technological factors on the transition toward CE in E-waste management systems. In order to find answers to the research inquiries, this investigation utilizes a qualitative research structure and abductive methodology.

There is not much research done about the role of DTs in enabling CE in E-waste management; therefore, a qualitative approach enables an exploration of rich and nuanced perspectives, knowing about the experience and perceptions of different actors involved in E-waste management, including firms providing digital technology solutions, municipalities, sustainability consultants and producer responsibility implementers. According to Fossey et al. (2002), in-depth interviews, observations, and document analysis, the qualitative design allows for a holistic understanding of the complexities and dynamics of the research topic. Therefore, this study selected this method in which the approach was formulating research questions, rich literature review, secondary data

analysis from the actors' websites, and in-depth interview of actors involved in managing E-waste management.

An abductive approach applied in this study involves using the concepts of the MLP framework. By applying the MLP framework as a theoretical lens, this study seeks to validate its applicability and examine the role of DTs and interactions between niches, regimes, and landscape factors in shaping the transition to a CE (F. W. Geels, 2002; Smith et al., 2005).

5.5. Data Collection

For primary data collection, interviewing relevant actors is necessary. Therefore, the first approach was finding relevant websites of actors and content. The author used the European Environment Agency website and WEE Forum to find relevant actors for E-waste management. Several white papers were reviewed to learn about E-waste management's current status and business model (see, e.g., (Dils, 2020)). Also, the author of this paper looked for interview subjects on Google, guest lectures from the Green ICT course, and sustainability events. About 45 companies were contacted, but ten actors agreed to have an interviewee for this study. A total of ten participants representing various key stakeholder groups were included in the study. These participants consisted of four digital solution providers, one sustainability consulting company, one individual from the public authority representing Copenhagen municipality, two experts, one collection scheme representative, and one Danish producer responsibility implementor. The interviews ranged from 30 to 60 minutes and were conducted online. The interviews were recorded to facilitate comprehensive data analysis, enabling the researcher to review the content and responses provided and observe the interviewees' non-verbal cues and reactions. This recording approach aimed to enhance the richness and depth of the data captured during the interviews.

This paper's author reviewed the actors' websites and reports and later confirmed it during the interview with the interviewee. The data was gathered from three actors' websites, a digital solution provider, an E-waste collection scheme (Recipo), and Danish Producer Responsibility (DPA). This approach allows the researcher to ask relevant questions and have in-depth interviews with interviewees.

Organization	Role	Organization size	Actor type accord to MLP
Transition	Sustainability and CE consultant	SME	Niche
Anonymous	Technology solution developer	SME	Niche
Waste Monitor	Technology solution developer	SME	Niche and regime
Anonymous	Technology solution developer	SME	Niche
Danish Waste Association	Public Authority	Large	Regime
Anonymous	Technology solution developer	Large	Niche
Copenhagen Municipality	Sustainability and CE expert	Large	Regime
Aalburg University	University professor	Large	Regime
Recipo	E-waste collection scheme	SME	Nihce
Danish Producer Responsibility	E-waste producer responsibility implementor	Large	Regime

Table 5.1 Breakdown of actors interviewees based on role

Given the multifaceted nature of sustainability and the involvement of various actors in E-waste management, this study adopted a multi-actor approach in the data collection process. This study aimed to capture a comprehensive picture of the complex dynamics and multiple perspectives involved in the transition toward a CE in E-waste management by including a diverse range of actors.

5.5.1. Semi-structured Interview

To answer the research questions of this study, the approach for this study was semi-structured interviewees. The interview questions were first drafted according to the secondary data and white papers, later based on information that the author of this paper found from conducting the literature review. Later the interview questions were categorized based on the analytical levels of the MLP framework to understand all the factors that impact the transition from the lens of MLP and also consider the bottom-up approach critiques of the MLP framework (Berkhout et al., 2004, as cited in Geels, 2011). In this way, different aspects, such as niche, regime, and landscape factors, are considered for the transition analysis. In the following, a sample of interview questions is included. The complete interview questions can be found in Appendix 1.

	Question	Description
General	Can you tell me about yourself, your organization and what role you have?	
Niche	What digital technologies are you currently using or developing in the area of electronic waste management?	Niche innovation stage
	How did you identify the need for such technologies?	Niche innovation stage
	In what ways have digital technologies facilitated or enhanced the recycling process and led to higher recycling rates?	Niche innovation stage
Regime	How have digital technologies impacted collaboration internally within the organization and externally with stakeholders? Problems between stakeholders: lack of awareness, fragmented communication channels, and lack of information sharing	Regime Transformation Stage
	What are the advantage of digital technologies in waste management? Example, like in cost of business, efficiency in better management or communication internally or externally	Regime transformation
Landscape	2. How do digital technologies impact public awareness about waste and proper waste disposal?	
	What policies or regulations exist to support/hinder the transition to a circular economy in E-waste management?	Governance level

Table 5.2 Sample of interview questions assigned to the MLP analytical framework

Folwing the initial and subsequent interviews, careful consideration was given to refining interview questions to ensure optimal clarity and understanding for the interviewees. A thorough background research process was undertaken to gather relevant information about the interviewees to enhance the quality and depth of the interviews. The background research was done either through LinkedIn or mainly through the company's website about the functions of the firms, technologies used, and the interviewee's role. This approach allowed the researcher to become familiar with the involvement and work of firms, enabling the researcher to tailor follow-up interview questions accordingly and have informed discussions with interviewees, thus enriching the overall quality of the data gathered.

The interviewees were provided with the interview questions and a concise summary of the research before the meeting to enhance their knowledge about the topic. Before starting the interviews, the researcher provided a brief introduction and the general purpose of the research. To ensure ethical consideration, the interviewee's permission was asked for

recording and mentioning their name and company name in this research. In cases where interviewees preferred to remain anonymous, their identity and company name were treated with confidentiality in this study. This approach upheld ethical standards aligning with principles of informed consent and data protection (Bryman, 2016b).

5.5.2. Expert Interviews

Experts interviews were conducted to validate and enhance the credibility of the gathered primary data from other actors involved in this research. Experts interviews were conducted with a professor from the university and a CE and LCA expert from the municipality of Copenhagen. These experts were selected based on their involvement with sustainability projects and deep knowledge of CE and DTs, which made them valuable resources for validating and collecting new data (Bogner et al., 2009). The university professor has been involved in a sustainability project in Brazil to help waste pickers make a good life by using DTs. The CE and LCA experts hase been involved in various sustainability projects in the Municipality of Copenhagen.

Validating data with the experts through interviews is a form of triangulation in this research. Bryman (2016b) defines triangulation as utilizing various sources, methods, or perspectives to confirm the findings of a research study. The expert interview was conducted in a structured and systematic manner. To achieve this, the researcher reviewed the collected data and identified points relevant to each interview question discussed with the experts during the interview (see as an example the summary of interview questions included in the following). By comparing and contrasting the insights of experts with the gathered data, this approach provides the opportunity to gain additional information that enriches the data. The expert's insights and perspectives were recorded, coded, and analyzed alongside the primary interview data. This allowed for triangulation and cross-validation of the findings (Bryman, 2016b).

	Questions from experts	Description
NIche	According to other companies' interviews (unified data for better decision making, tracking of product life cycle, enhanced reporting, reduction in business cost), what are the potential of DTs for CE, what do you think, and how do DTs impact the development of CE in E-waste management?	Niche, innovation stage

Regime	Communication between stakeholders is essential for enabling CE. Lack of awareness, fragmented communication channels, and lack of information sharing are the problems that DTs can improve; according to the interviews that I did, what do you think about how DTs impact collaboration internally and externally with stakeholders to enable CE?	Regime Transformation Stage
Landscape	European Green deal, and extended producer responsibility are the regulation for support of CE, in you are opinion, what policies or regulations exist to support/hinder the transition to a circular economy in E-waste management?	Governance level
	What policy changes do you think are necessary to encourage the use of digital technologies in managing electronic waste in a way that promotes a circular economy?	Governance level

Table 5.3, Sample of expert interview questions for sustainability experts

5.6. Data Analysis

In this paper, thematic analysis has been used to analyze the primary data gathered from the interview. According to Clarke et al. (2015), thematic analysis is a qualitative method used to identify, sort, categorize, and analyze themes found in the data set. In other words, researchers can employ an iterative process to interpret essential aspects of research data in an organized and structured format. Identifying themes in thematic analysis can be accomplished through two distinct methods. The first one is inductive, in which a theme emerges from the data without any pre-existing theoretical framework. In this method, themes can be drawn up based on patterns and meanings observed in the data. The second one is deductive, in which themes are identified through the lens of a theoretical framework (Braun & Clarke, 2022). This research employs an abductive approach to analyze the data and generate meaningful themes. The data analysis process prioritizes exploring the data itself, allowing it to guide the identification and development of themes. Once an overall understanding of the extracted themes is established, they are categorized according to the three analytical levels of the MLP framework: landscape, regime, and niche.

The thematic analysis involves several processes involving data collection, familiarizing with the data, initial coding, obtaining themes, reviewing and refining themes, and creating a narrative (Guest et al., 2012). To get a deeper understanding of the data and extract meaningful insights, the author of this research followed the mentioned steps for

analyzing the data. The analysis followed a series of steps: Upon completion of the interviews, transcription was performed using Fireflies software. In the initial step, the transcripts were extracted and imported into the software RemNote for familiarization, note-taking, and memo creation. A summary of each quote was generated to facilitate a better understanding of the content and meaning of the data. The subsequent step involved the start of the initial coding process, whereby the author assigned codes to the quotes to capture the main points. In the third step, the researcher reviewed, modified, and added new codes as necessary. During this phase, factors derived from the MLP framework that influenced the niche and regime were considered. The coding process resulted in the identification of 70 codes. Moving to the fourth step, themes were generated by examining the codes and their content, merging similar codes, and categorizing them as main and sub-themes. In this phase, the three analytical levels of the MLP framework (niche, regime, and landscape) were considered. Finally, each theme was thoroughly reviewed and cross-checked to ensure appropriate naming and alignment of the excerpt's meaning with the respective theme.

5.7. Limitation

In this study, the Guba framework was employed to assess the validity and trustworthiness of the research findings, encompassing four fundamental elements: credibility, transferability, dependability, and confirmability (Lincoln & Guba, 1985). According to Lincoln & Guba, (1985), credibility pertains to the degree to which the results precisely depict the truth and reflect the reality of the studied phenomenon. Transferability shows that the findings is replicable in diverse contexts by other researchers. Dependability means that the findings are replicable and consistent across different situations. Confirmability highlights that the research findings are grounded in data and not influenced by the researcher's biases.

To ensure credibility, this research conducted data triangulation; first, the author of this paper reviewed the reports and websites of three actors and cross-checked them with the interviewees during the interview. Also, the gathered data from the interviewees was cross-checked and tested with two sustainable experts who participated in this research. To ensure transferability, a code book (see, Appendix 3) is created and explains the meaning of each primary and subtheme; also, the methodology process is explained in detail,

allowing other researchers to judge the findings in another context. However, qualitative research can not aim for replicability by design (Bryman, 2016a). Also, the author of this research has a professional background in software engineering which may present a bias in interpreting the result because his experience may impact the belief in DTs' positive impact. To maintain an open and balanced perspective, the author ensures that the interview questions are neutral and not leading and have been careful in analysis not to overstate the DT's potential or ignore the challenges and drawback. The author also got feedback from the tutor and supervisors regarding the interview questions. This reflexive approach strengthened the credibility and addressed the biases issue.

This study acknowledges several limitations. One limitation is related to the empirical implementation of the MLP, which posed challenges in distinguishing between the niche and regime levels in certain instances. This issue has also been subject to criticism from other researchers (Genus & Coles, 2008). Nevertheless, efforts were made to identify factors indicating stability and less stability while distinguishing niches from regimes, as proposed by F. W. Geels (2011). However, the precise criteria for clarifying stability and less stability remain somewhat ambiguous. Another limitation arises from not having EEE producers and E-waste recyclers as paritcipants of this research due to time constraints. Producers' perspectives could have add to the depth of this research. Nonetheless, interviews were conducted with actors representing both the production and user sides, aligning with F. W. Geels' (2004) recommendation to encompass diverse actors shaping the socio-technical system. This approach enhances a nuanced comprehension of the role played by niches and regimes in adopting CE principles within the E-waste socio-technical system.

6. Empirical Results

In this section, I will provide and analyze the findings from the interviewees and data that the author of this research gathered from reports and websites of different actors. In this section, first, the demographic of the interviewee is explained. Then the finding is discussed, which has several subsections, generally divided into landscape, regime, and niche; later, the discussion and summary of this chapter are provided. Some organizations interviewed for this research are preferred to be anonymous. Therefore confidentiality is considered here.

6.1. Demographic

To consider the bottom-up approach basis of the MLP framework and have a nuanced understanding of factors that impact on the transition of CE in E-waste management, not only digital solutions providers for E-waste management but also firms and organizations which are involved in E-waste management are interviewed. However, most firms are digital solution providers (four out of ten), and the rest are firms and organizations involved in E-waste management or sustainability projects. Particularly one sustainability consultant SME, two public authorities from the Danish waste association and Copenhagen municipality, one E-waste collection scheme, one producer implementor for E-waste, and a professor university interviewed. Technology companies are developing innovative and digital solutions for general waste management, including E-waste. For instance, a firms developed integrated digital solutions for the whole administration process of waste management, including waste collection, route management, reporting, and financial model. Transition, a sustainability consulting company, among various other sustainability projects, implemented a product service system business model for a manufacturing company called Eurocan. Danish waste association is a political interest organization that collaborates with various organizations to reduce waste and improve transparency in waste management sectors. Recipo is a collection scheme assisting procures in the collection and recycling of E-waste according to EPR. Lastly, Danish Producer Responsibility (DPA) is a non-profit organization that developed a communication platform for registering producers and collecting data about E-waste generation, collection, and treatment.

Interviewee	Interviewee name	Role	Years of Experience	Organization
1	Mathias Majlund	Consultant and sustainability expert	3 years in the industry	Transition
2	Anonymous	Innovation manager	6 years in the organization	Digital solution provider
3	Matthias Schwarzer	Founder of the company	7 years in the organization	Waste Monitor
4	Anonymous	Project manager	-	Anonymous
5	Anonymous	Sustainability expert and project coordinator	3 years in the organization	Danish Waste Association
6	Anonymous	Expert of SAP system, life cycle in waste and recycling	15 years in waste & recycling	Digital solution provider
7	Sarosh Qureshi	LCA and CE expert	4 years in the organization	Copenhagen Municipality
8	Jens Myrup Pedersen	University professor	-	Aalburg University
9	Anna Viktorsson	Business Coordinator	3 years in the organization	Recipo
10	Johny Bøwig	Director of DPA	-	Danish Producer Responsibility

Table 6.1 Interviewees overview

Interviewee 1 is a sustainability consultant who advises companies on becoming more sustainable; one of the focuses is CE. **Interviewee 2** is the innovation manager in the company, but he hase worked as a business developer and manager of application development. **Interviewee 3** is the founder of the company. **Interviewee 4** is a project manager in the company. **Interviewee 5** is working as a sustainability expert and project coordinator. **Interviewee 6** is a market intelligence officer in the company, but he has 15 years of experience in software solutions and technology, waste, and recycling. **Interviewee 7** has been involved in various sustainability projects in the municipality of Copenhagen. **Interviewee 8** is a university professor and hase been involved in a sustainability project to improve waste pickers' life through DTs. **Interviewee 9** is a business coordinator who collaborates with recyclers, and **Interviewee 10** is the director of Danish Producer Responsibility.

6.2. Findings

The finding of this study is based on data gathered from 10 interviewees and documentary such as reports and websites, which can be found in Appendix 2. The primary data were analyzed, and themes were derived from the data. After assigning codes to the data and merging similar codes, 12 main themes and 12 subthemes were identified. The whole process of thematic analysis, which is mentioned in the methodology section, was followed. The themes were later categorized based on three analytical levels of MLP, landscape, regime, and niche. During this categorization process, factors associated with each level mentioned in the operationalization of the MLP framework (see operationalization of MLP framework for understanding factors of each level), were considered to ensure a comprehensive analysis and categorization of the themes. Specifically, external factors such as climate change, policy, and social awareness, which influence the regime, are considered. The regime level encompasses the existing practices, norms, policies, and challenges within the E-waste management sector. Moreover, at the niche level, emphasis is placed on innovative solutions, technologies, or practices that play a pivotal role in embracing CE principles. Concerning technology, the regime has already integrated specific digital technology solutions. A classification was made based on innovativeness to distinguish between themes pertaining to technology at the regime and niche levels. Specifically, digital technology solutions enabling CE practices were categorized as belonging to the niche, while those outside this scope were considered part of the regime.

MLP analytical levels	Main themes	Sub themes
Landacpe	Climate change	-
	Social Awareness	Social behavior
		Clients behavior
		Educational programs
	Policy	-
	Market demand	-
Regime	Established procedure	Actors and its responsibilities
		Collaboration
		E-waste collection
	Established procedure problems	Quality control
		Policy limitation
		Need for policy

	Role of DTs in operational efficiency	Role of DTs in logistics
		Role of DTs in collaboration and information sharing
	Resistance to change	-
Niche	Strategies for Reduction of E-Waste	-
	Potential of DTs in enabling CE practices	-
	Role of DTs in raising consumer awareness	-
	Barriers to DTs	Limitation of DTs
		DTs implementation challenges

Table 6.2**,** Themes and subthemes extracted form primary data

6.2.1. Landscape

The theme "Landscape" encompasses the external factors that influence both the regime and the niche within the context of this study. This theme comprises three distinct subcodes, namely climate change, social awareness, educational programs, and policy.

6.2.1.1. Climate Change

The theme "climate change" describes that environmental concerns, such as the scarcity of raw materials and geopolitical instability, have pressured the existing regime to rethink their practice and consider adopting sustainable business models.

Three interviewees expressed a similar perspective, stressing the collective recognition that embracing a sustainable or CE business model is imperative for maintaining our current standard of living due to the constraints posed by resource scarcity, high commodity prices, and geopolitical instability. Consequently, climate change promotes a shift towards sustainable and circular practices.

> *“ [...] basically as sustainability has really taken off, as the circular economy has really taken off. And there's a geopolitical instability and the need to recycle to basically stop raw material extraction, which is about 45% of GHG emissions in the supply chain. And materials mishandling, I think is about 70% of GHG emissions in the supply chain. So with all these socio legal, economic, political and technical impacts in the world, there's been a necessity to have waste treat waste as a resource and utilize recycling to keep materials in circulation.”* - Interviewee 6

"I think they have to implement circular economy. We have to do that to maintain a certain level of luxury that we have because the resources are getting more scars and the prices are going up. So we have to start thinking of new ways to produce goods and to look at our value chains." - Interviewee 7

"Yes, I think actually some of them are really looking hard to find new solutions because they know they had to reduce their emissions [...] That's when they look into new way of doing it and that's when they come to us as a consultant and come and saying what can we do here that we haven't thought of? Which new methods out there can we use?" - Interviewee 1

Moreover, one interviewee highlighted that adopting environmentally friendly business models also offers a distinctive value proposition for firms.

"That means that their environmental footprint is actually less than the other models in the traditional models because they won't have to purchase new parts all the time because they're going to develop one that is less longer. So for them, it's actually a way of the unique selling point is an environmental one thing that you will now do." - Interviewee 1

6.2.1.2. Social Awareness

The theme "social awareness" describes society's contribution to promoting sustainable products and better recycling of waste. However, there is a need for educational initiatives, clear communication, and incentives to bridge the gap between awareness and action, ensuring that individuals understand the underlying reasons and benefits of sustainable practices. "Social awareness" includes three subcodes which are "social behavior", "clients behavior," and "educational programs," which will be discussed later.

One of the interviewees emphasized the increasing societal awareness of sustainability and the growing interest in green products. This awareness and interest exert pressure on companies to reevaluate their activities and business models.

"I think, you know, there's all these what's called analysis or surveys done each year saying that more and more consumers want greener products. I think what we see is that they would require us improve that they actually are greener." - Interviewee 1

Two other interviewees support the significance of social awareness in influencing the adoption of sustainable business models. They highlighted that the younger generation demonstrates more interest in sustainability practices.

> *"So the culture is changing because your. Generation already think in the green approach."* - Interviewee 2

> *"There is a bigger acceptance of and it has a value. It's a kind of status to reuse products and to look for sustainable material. So I think this has a social impact."* - Interviewee 3

Most interviewees acknowledged the presence of social awareness regarding the proper sorting of waste, particularly not disposing of E-waste in common bins. However, they also mentioned that not everyone is taking action to recycle their E-waste due to a lack of understanding about the benefit of E-waste recycling, such as transforming waste into new materials and reducing raw material extraction. In response to this challenge, interviewees 2 and 7 proposed using DTs to raise social awareness about financial incentives of E-waste and taxing people who are generating E-waste more.

> *"[...] I think most citizens in Denmark, they are into the sorting. They have learned that they have to sort, they will also sort electronic waste."* - Interviewee 5

> *"I think the awareness is fairly large. There are a lot of people aware. But I think it's more interesting to see how many people act upon awareness because I think a lot of people are aware of what's going on and all these different things."* - Interviewee 7

> *"[I] Think people are aware to some extent, but I think that they're aware that they shouldn't, for example, throw e waste in the regular trash because it needs to be recycled. But I don't think that everyone's aware of why it needs to be recycled and that it's made into new material and that if we don't recycle the e waste that we have, we need to mine for more metals. For example."* - Interviewee 9

Interviewees 2 and 7 agreed that a notable level of social awareness exists concerning the appropriate disposal of waste. However, they emphasized the need to encourage the public to take tangible actions toward waste management by using DTs and putting taxes.

"[...] So I think the awareness is there, but it's not very convenient. So we need to make it more convenient and that could happen through digital platforms" - Interviewee 7

"People must understand that it's not easy way to put the waste everywhere. Is. Something impact the money. Because we are in the money era. The only way to change their [mind] is to take money who don't do the right action at first" - Interviewee 2

6.2.1.2.1. Social Behavior

Social behavior is the sub-theme of "social awareness", explains the intention of individuals to not recycle their E-waste, despite being aware of the importance of proper sorting and disposal.

Two interviewees emphasized that people are generally reluctant to return their E-waste to designated collection points, particularly when it comes to smaller electronic devices that can be stored easily at home. This behavior reduces the likelihood of E-waste being recycled and reused effectively.

"I would say normally they're really well informed but there's actually a little bit special about this electronic waste, [...] we can see that people stores it, they store it at home. They don't want to hand it over because maybe they have a child or maybe my uncle or maybe so they kind of keep the waste instead of giving it back. And that's of course a problem if you want to have the circular economy because as longer you store it at home and don't use it as less is the opportunity actually that some of the parts could be good for reuse option" - Interviewee 5

"I think that's a big issue. There was a study in Sweden a couple of years ago where they basically investigated why mobile phones aren't collected to the extent that maybe they should be. And it was concluded that every Swidish had maybe, I think around three old phones at home on average. So yeah, I do think that it's a big issue and especially maybe for smaller equipment that's easy to store at home." - Interviewee 9

6.2.1.2.2. Clients Behavior

Clients behavior is the sub-theme of "social awareness", which describes that small and medium-sized enterprises (SMEs) show a greater tendency to adopt CE business models or

strategies. This statement is confirmed by two other interviewees who emphasized the existence of general awareness among companies, especially among the younger generation, regarding the concept of CE. According to these interviewees, companies are transitioning toward sustainability and CE business models. Interviewees highlighted that SMEs are likely to embrace CE practices if they perceive the benefits associated with it's implementation.

> *"product is actually pulled out of the waste stream and having a second life. But the business model are driven by mostly small companies, more idealistic people who is actually making up maybe a good small business for themselves."* - Interviewee 10

> *"I think we are in a transition period right now in the sense that more and more companies are aware that they need to change the way business are done. So business usually is not good enough anymore. But I still think that there still needs to be some explanation on the benefits of why should they do and how should they do it. [...] So I think that might be a challenge. I think in general, companies are aware that they need to change, they're looking for solutions and I think circular economy could be one of them"* - Interviewee 1

> *"It's often a good chance if there is new person in the company. Like if you have a family based, family owned company and the old man is going out of the company and the next generation is coming. This is always a good point. To start."* - Interviewee 3

6.2.1.2.3. Educational Programs

The "educational programs" theme highlights the diverse approaches employed by various actors to raise social awareness regarding the proper recycling of E-waste. Specifically, two interviewees discussed implementing educational programs to increase public awareness and knowledge.

One interviewee representing Recipo mentioned the organization's collaborative campaign with other stakeholders involved in E-waste management. The campaign sought to educate individuals about the importance of recycling E-waste and provide information on where and how to dispose of such waste properly.

"Yeah, so it's an old project. We don't run it in our regime anymore. It's still happening this year. But we're just contributing in part of paying for it. Previously we've driven the project ourselves and the idea is basically that it's a way to reach the consumer because that we can collaborate within our industry to reach the consumer. Because for us it's not important that the consumer knows who receipt or are familiar with our brand. But it's important that they know how to recycle properly, where they can recycle and why it's important. Okay, so it's basically like joint marketing campaign aimed at consumers." - Interviewee 9

Another interviewee emphasized the importance of raising awareness about E-waste management. According to the interviewee, municipalities in Denmark have organized education programs at various locations, including kindergartens, schools, and community events. These programs aim to educate and inform individuals about the significance of proper waste recycling including E-waste.

"Of course, the municipality has a role to inform the citizens how they should sort. [...] But there's also a lot of other initiatives. There's so many possibilities for kindergarten kids and school kids to go and visit and to learn. So they really try on every level to get into decisions. Also, if you have a kind of town festival or whatever, you will often see the waste department trying to explain why you should sort and how you should sort and that the waste bin is in two compartments and all these kind of stuff. So there's a lot of communication not only this kind of written rules but also a lot of other ways to explain to the systems what to do." - Interviewee 5

6.2.1.3. Policy

The "policy" theme highlights the role of policy measures in exerting pressure on regimes to adopt CE business model strategies and better E-waste management.

The interviewees shared their perspectives regarding the effectiveness of EPR in holding producers accountable for their products throughout their lifecycles. This accountability was seen as a driving force for firms to adopt CE practices. However, it was also acknowledged that the successful implementation of EPR is crucial and should be carefully considered to ensure its effectiveness and optimal outcomes.

"I definitely think that the law about extended producer responsibility is definitely going to assist in that because then you require companies to think about what's going to happen to a product once your customers are done using it. I think that's [...] area of regulation that's going to help with more Circulate funding, but then you cannot ignore how it's going to be handled and applied" - Interviewee 1

"extended producer responsibility legislation plays a crucial role in controlling waste generation. By holding producers accountable for the environmental impact of their products throughout their lifecycle, this legislation encourages responsible waste management practices" - DS 1

The positive impact of EPR was affirmed by Interviewees 7 and 5, who highlighted the shift in responsibility from the municipality to the producers of the products and mandate producers to take responsibility for properly disposing of E-waste and report on their environmental footprints, and adopt CE practices. .

"I think that the responsibility should be with the producer. So if a product is not being used anymore or it has reached the end of its life, it should go back to the producer and the producer should break it down and make new materials out of it or get it recycled" - Interviewee 7

"But I think maybe what it is 18 years ago or something, we had this producer responsibility in Denmark, and at that point, the municipalities are only in charge of collecting this electronic waste. And then we will hand it over to the producers or these organizations that the producers have established to take care of their responsibility." - Interviewee 5

Another interviewee asserted the importance of EU regulations like digital passports and the Corporate Sustainability Reporting Directive (CSRD). Particularly, according to CSRD, large companies and some SMEs must report their impact on the environment and other sustainability issues. In this way, it results in better transparency between stakeholders, and the firms will have a solid understanding of past footprint and think about solutions for reducing it for the following year.

"So the EU has just launched that they wanted to create this digital passport for instance. So I think that's stepping stone towards that. You might also learn of some

of the new EU regulations called CSRD where you have to have companies report on the environmental and social [incentives]. [...]. But in the future they would have to report each year and any company will always want to better than they were the previous year. So I think what we'll see is that once they learned how their scoping looks and how they how much they need don't need to look into a solution to reduce it next year so their stakeholders or shareholders will be happy" - Interviewee 1

Interviewee 3 and Data Source 1 discussed the significance of the European Green Deal and Circular Economy Action Plan, which stresses the importance of sustainability, and CE strategies including reuse and recycling. These regulatory initiatives highlight the need for companies to adopt DTs to comply with sustainability requirements. The overall understanding is that incorporating DTs into their business operations is essential for aligning with the CE principles to comply with the regulation.

"In Europe, the Green Deal legislation has set ambitious targets to achieve net-zero greenhouse gas emissions by 2050. [...] These policies promote the principles of reuse and recycling, aligning with the transition toward a circular economy. To ensure compliance with regulations and policies, waste management companies need a comprehensive overview of their business processes, which can be achieved through the adoption of digital technologies." - DS_1

Interviewee 3 and Data Source 1 also highlighted the adoption of DTs by waste management companies in order to comply with policy requirements. Firstly, the development of digital solutions was driven by the legal structure and the need for improved process documentation in Germany. Additionally, in the UK, the implementation of the mandatory waste tracking (MDR) policy necessitates information sharing among waste management actors, and the adoption of DTs is seen as a viable solution for easily meeting the policy's compliance demands.

"[...] there were some changes in the legal structure in Germany and the task to improve documentation within the processes. And one of my co founders, he has a waste management company, so a family company with, I think, ten people. And he was looking for software to be able to documentation to go" - Interviewee 3

"In the United Kingdom, the implementation of the mandatory waste tracking (MDR) policy has underscored the significance of digital technologies in waste

management. [...] The MDR mandates timely information sharing among various actors involved in waste management, including waste importers, exporters, recyclers, and collectors. To comply with these requirements, digital waste management systems like ISB Global offer effective solutions" - DS_1

6.2.1.4. Market Demand

The main theme of "market demand" explains the degree of preparedness and receptiveness the market exhibits about adopting CE business models and DTs. This theme explores the factors and dynamics that influence the demand for CE and DTs within the context of E-waste management.

According to Interviewee 1, adopting sustainable business models within firms is rising, increasing demand for DTs. The interviewee further highlighted that an increasing number of companies are currently developing tools to collect and analyze data.

> "as you see now, there's a lot of companies developing ESP tools for you to collect data. But there might be companies, once we see them more and more adapting distributed business model, they might see a gap for certain need of digitalization" - Interviewee 1

However, interviewee 8 mentioned that the general awareness and for adopting CE business model is there among the firms but what to use and how to get benefit out of it is a challenge for some of the firms. The interviewee said, "But I think the biggest problem is to actually know what to use and when to start using it. Because the businesses, their business as usual is doing whatever they do. So it's not [necessary] to be experts on [the] CE or how that we can manage our waste at the end of the life of a product or whatever it is".

Interviewees 2 and 3 both concurred that there is a notable market demand for adopting DTs within firms, driven by the increasing importance of sustainability. The interviewees emphasized that companies are motivated to demonstrate their commitment to sustainability to the public, as it aligns with the interests and concerns of people. In this context, DTs can serve as a bridge, enabling companies to showcase their sustainability efforts and engage with consumers.

"sustainability has an impact on producing companies. So they are writing down more and more sustainability documentations and people are requesting more, okay, how is the product produced? People are more there's a trend of using reuse products and I think this has a market impact. And and I think digital solution can yeah, can build bridges" - Interviewee 3

"The market is ready to take is what we say before the economic support" - Interviewee 2

Interviewee 6 highlighted that a significant portion of waste management companies, approximately 70 percent, still need to digitize their operations and continue to rely on manual transactions. This traditional approach entails high costs and inefficiencies. However, the interviewee expressed the intention to address this challenge by offering an integrated software solution tailored to the specific needs of the waste management industry.

"And we had a small sample in that research, and what was fed out was I think almost 70% are still conducting manual transactions" - Interviewee 6

"But what we're trying to do is change the perception. So rather than have a short term attitude" - Interviewee 6

6.2.2. Regime

In this section, the main themes, and subthemes that clarify the regime roles, norms, and practices within the context of this study will be discussed.

6.2.2.1. Established Procedure

The main theme, "established procedure," provides an understanding of the current business processes and activities within the existing regime of E-waste management. This theme encompasses several subthemes, including "Actors and its responsibilities", "collaboration" and E-waste collection" which will be explained in the following

6.2.2.1.1. Actors and Its Responsibilities

Actors and responsibility is the subtheme of "established procedure," focusing on the identification and delineation of the actors involved in the management of E-waste and their responsibilities.

Interviewee 10 and DS_4 mentioned that the DPA registration platform is a communication system that collects data about the amount of EEE put in the Denmark market, E-waste taken back, reused, and recycled, which is accessible publicly and in the borders that authorities can verify if EEE importers are registered with DPA.

> *"[...] And then naturally we also have to do a support and the support is how the users have to use or should use our systems which are web based system working for registration and reporting"* - Interviewee 10

> *"DPA has been set up to establish systems supporting the monitoring of the targets set up in the directives and associated national law, giving at the same time producers the best opportunities for contributing actively to the attainment of those targets in their commercial activities."* - DS_4

According to interviewee 10 and DS_4, the responsibility of DPA is to calculate the amount of E-waste that the collection scheme or producer has to collect from the allocated collection points based on the category of E-waste the producer puts in the market.

> *"At DPA, we calculate the distribution among producers of quantities of end-of-life electronics and batteries to be collected at the recycling centres. The geographical distribution is based on producers' market shares and the mandatory take-back obligation."* - DS_4

> *"And the way we are doing it is actually naturally by these reporting that we are receiving once a year. But in reality we have pinpointed the places, the geographic places that each producer or their collective schemes have to go to around in Denmark because we have allocated [...] each single municipalities by the category or the fraction as it's called when it's been waste."* - Interviewee 10

Interviewee 10 mentioned that DPA is responsible for reporting to the Danish EPA. They then have to report to Eurostat, which monitors the performance of E-waste collection and treatment performance in all European countries.

> *"And though all those data we naturally have in our system, but also we report them to the Danish EPA because the Danish EPA have to deliver the exact same reporting to the Eurostat because Eurostat on the European level are actually monitoring how is the performance in each European country"* - Interviewee 10

According to interviewee 10, 9, and data sources, one another actor in the context of E-waste management is the producers of EEE. These producers are bound by specific obligations, including the requirement to report annually to the DPA regarding the quantity of EEE they put into the market and the amount collected from assigned E-waste collection points. Additionally, producers are responsible for collecting E-waste from professional users if they have sold EEE products to them. They are also tasked with ensuring proper labeling of EEE products, indicating that they should not be disposed of in regular bins, and providing information to professional users on how to return the E-waste.

> *"Yes, well, first of all it's part of the legislation that the producers should report once a year how much they put on market. [...] report how much they have been taking back from the market"* - Interviewee 10

> *"but also some of the producers do their own collection in the process of selling new equipment"* - Interviewee 10

> *"Of so basically our producers report to us what they sell and they also pay a fee based on the product that they put on the local market"* - Interviewee 9

> "*Private equipment is covered by allocation schemes and can be discarded under the municipal collection scheme. The producer responsibility for professional equipment entails a direct obligation on producers/importers to take backequipment free of charge when it becomes waste."* - DS_2

> *"Producers of electrical equipment are under the obligation to inform users, among others, about correct disposal"* - DS_3

Collection schemes are an important actor within the E-waste management system. Their main responsibility is to collect household waste from the designated collection points assigned by DPA. Producers may have agreements in place with these collection schemes for the proper collection and handling of E-waste. The collection schemes collect the E-waste from the designated points upon request from the municipality.

> *"I guess, the way that we collect the waste. Because now it's being collected as something that needs to be recycled, which means that it doesn't matter if it has some scratches on it. From the transportation, for example."* - Interviewee 9

"So that we for instance, we are saying to a collective schemes well you collective schemes a for the next twelve months you should go to this and this municipalities and you should take back this and this fractions from the place.[...] So they have exactly the obligation to go out there. Each time that the munchipality call for emptying out the containers or the trays, then the collective scheme are responsible to send out somebody to fetch the waste and place a new empty container or some new empty trays" - Interviewee 10

The collection schemes also have a contract with the Environmental approved recyclers for recycling and treatment of E-waste. Collection schemes must report back about the treatment, reuse, and recycling of collected E-waste from the collection points to the DPA.

"And then for the amount of the waste they have to do the treatment later on, or they have to have some subcontractors who are doing the treatments and what they are doing with the electronics, they also have to report to us. So they are reporting each single subcontractors that they have, how much they put into their system, how much is put on to treatment, how much is coming out in the other end, so how much have been reused or what is the results of the treatment process" - Interviewee 10

"But there's also a large amount of the waste that's collected from municipal collection points and that's collected by a different PRO. But we take some of the costs of this recycling based on our market share or I guess our customers market share" - Interviewee 9

6.2.2.1.2. Collaboration

The subtheme of "collaboration" highlights the significance of collaborative efforts among various actors in adopting CE business models, adopting innovative technologies, and improving E-waste management. The interviewees emphasized the need for cooperation and partnership between different stakeholders, including producers, collection schemes, reuse partners, and authorities. By working together, these actors can share knowledge, resources, and expertise to drive the transition towards more sustainable practices.

The majority of the interviewees in the study concurred with the notion that collaboration is a vital component in facilitating the CE. Interviewees 1 and 7 highlighted the existence of multiple actors within the value chain, asserting that the objective of enabling CE could

not be accomplished solely by individual actors. This trend of collaboration between stakeholders is getting better recently.

> *"The very fundamental principle circular economy is that you work with more partners along the value chain. So this old idea of you owning the entire value chain and you owning the is simply not going to be an option anymore. If so, you need to be a really big company. But now you need to manage the entire lifecycle of the compact of the product, both sourcing production, distribution, sales and then use of products as well as how you're going to handle it at the end of life. And then you should probably recycle them going back into your value chain or someone else value chain. So I think in the future companies will need to collaborate much more than what we're seeing today"* - Interviewee 1

> *"Yeah, well, I think something that's very essential when we talk about circular economy is that we start thinking of everything in a value chain. You cannot think of your business as well, it's a link in the value chain. Right. And you cannot just look at it as a whole system in itself. It is a system in itself, but it's a part of our value chain"* - Interviewee 7

The interviewees emphasized the significance of collaboration within the E-waste management sector, particularly regarding the involvement of producers, waste collectors, and recyclers.

> *"Yeah, I think it's very essential that the producers of electronic waste or different kind of waste, they collaborate with different collectors and recyclers because the company itself, they cannot do all different things, but they need to collaborate and pay for it"* - Interviewee 7

> *"Continues changing the mining to manage it best from the houses to the industry the waste. If not, we continue to have a problem to consider"* - Interviewee 2

The interviewee agreed with the importance of collaboration by saying that close communication between actors is necessary for transitioning toward CE.

> *"It's great. I think that close communication between the actor is mandatory for working out this up to the next level"* - Interviewee 10

6.2.2.1.3. E-waste Collection

"E-waste collection method" is the subtheme of "established procedure". This subtheme explains the E-waste collection methods.

During the interviews, E-waste collection methods were discussed, highlighting two distinct approaches. The first method involves the collection of E-waste from households, primarily facilitated by the municipality, which provides designated collection locations. The second method pertains to E-waste generated by professional users, wherein the responsibility for collection lies with the producers or collection schemes. In these cases, collection points provided by the producers or collection schemes, allowing for the proper disposal and management of E-waste generated by professional users.

> *"Yes. And we collect household e waste. We occasionally might help our customers with professional e waste also, but that's out of the ordinary. I'd say almost all of our collection is household waste"* - Interviewee 9

> *"it really depends on what kind of electronic waste we are talking about, [...] these companies that are responsible for reusing or recycling, like, different components. So as a municipality, we're basically only collecting from households, and then businesses have their own collection schemes"* - Interviewee 7

> *"So the collection point that we collect from, which is basically electronic stores there in some places we have containers for larger equipment like freezes and stoves and things like that. And we also have some cages in the stores, the back office of the stores."* - Interviewee 9

The method of collecting E-waste from municipality collection points is characterized by traditional practices, with limited utilization of Internet of Things (IoT) devices to gather information about the fill-level status of containers.

> *"So we've tried some different sensors, but unfortunately, since the containers are stored inside. It's been difficult to find a sensor that meets our needs"* - Interviewee 9

> *"No, we don't. It's awful. We have some kind of not even containers, I don't know the Danish English word is some kind of boxes, metal boxes that we are provided with from the producers or the organisations. They provide us with these collecting boxes that we use in our recommending sites and they are not really good. And we*

have asked them to try to develop some better collection equipment" - Interviewee 5

According to Interviewee 9, there is a significant portion of E-waste that is collected through unofficial channels, accounting for approximately 40 percent of the total. This indicates a challenge in ensuring the proper recycling and reuse of E-waste

"It's 60 somewhere percent. But that's I guess collected through official channels because I do think that a lot of the waste is collected through channels that aren't the correct legal ones." - Interviewee 9

6.2.2.2. Established Procedure Problems

The main theme of "established procedure problems" explains the challenges associated with the existing business processes of incumbents in E-waste management. These challenges encompass various aspects such as unstandardized collection methods, the reluctance of consumers to properly handle E-waste, high costs associated with recycling, and the existence of unofficial channels for E-waste collection.

According to Interviewees 10, 9, and 5, the collection method for E-waste is not standardized, leading to potential damage to the products when consumers dispose of them in the containers at collection points. This lack of standardization poses a challenge, as products that were previously functioning may become inoperable during the collection process. Interviewee 9 agreed with mentioned point and further emphasized the importance of establishing partnerships for product reuse, as solely focusing on recycling limits the opportunities for reusing products that are still functional, this may happen during collection, for instance.

"And that was the reason why I gave it the expression the graveyard syndrome. People don't like actually to put them there. They would be more delighted actually to deliver the product when it's still functioning into another system which not is so massive or hard of rough in their handling of the product" - Interviewee 10

"No, so I think in general, I think that everything that we do is part of the circular economy. But I think that we could definitely better at, for example, reusing more products instead of recycling them. [...] Yes, but I think that we could perhaps or we have also looked at finding partners for reuse so that we can reuse more products.

But this also kind of has to change, I guess, the way that we collect the waste. Because now it's being collected as something that needs to be recycled, which means that it doesn't matter if it has some scratches on it. From the transportation, for example" - Interviewee 9

"And then if you want to reuse this electronics, we also don't think it's a really brilliant idea just to throw everything into this kind of collection equipment that we are provided with" - Interviewee 5

In addition, Interviewee 5 agreed with the point that the lack of standardized collection methods for E-waste poses challenges. She highlighted that consumers are often reluctant to bring their E-waste, particularly small devices that may contain sensitive data, to the designated collection points. This hesitation stems from concerns that these devices could be easily stolen, resulting in the potential loss or misuse of personal information. The fear of data security discourages individuals from disposing of their small electronic devices at collection points, and they prefer to keep such items in their houses. Even if they dispose of it, sometimes they crush it, making it difficult to reuse or recycle.

"We have one trouble is that it's easy to steal. There's no guarantee that if citizens would leave a laptop or a phone that is not stolen by the next so we would of course like to have some other collecting equipment that you cannot take stuff out again." - Interviewee 5

"I know that it's not safe just to put it in the bins at the recycler station because it's value resources.It can be stolen, my data can be stolen with it. [...] What I'm supposed to crush, what I'm supposed to demolish before I hand this over. And of course when I demolish this kind of items I cannot be reused. Maybe it's also more hard to recycle some important parts" - Interviewee 5

The interviewees pointed out that the rate of reuse for E-waste is relatively low. This is attributed to the tendency of individuals to store their E-waste at home or in drawers, reducing the opportunities for reusing these electronic devices. Additionally, interviewee 10 highlighted that consumers, particularly professional users, often prefer to sell their E-waste for personal gain rather than returning it to the producers as intended. This practice is not favored by the producers, who aim to collect the E-waste back from professional users for proper recycling and resource recovery

"Yes, I think that's a big issue. There was a study in Sweden a couple of years ago where they basically investigated why mobile phones aren't collected to the extent that maybe they should be. And it was concluded that every Swidish had maybe, I think around three old phones at home on average. So yeah, I do think that it's a big issue and especially maybe for smaller equipment that's easy to store at home" - Interviewee 9

"One problem is that the citizens actually don't. They kind of store a lot of stuff in their homes or in the summer houses, so they don't deliver enough" - Interviewee 5

"For companies it's a little bit different then they only have to take back what they have actually sold back in time [...] But what we see in reality very often is that if you look at how much they take back those company selling products to other company, business to business product, they take very little back. And why is that? Well, the basic and I think the most important explanation is actually that the end user of the products, they don't have to deliver back the obsolete product when they have reached the end of life position. They have bought the product, so they have the ownership. And what they very often do is actually that they are selling the product to the recovery industry so they have an income of selling their end of life. So the producers having very few amounts or small amounts back in most of the cases and that is well, naturally it's nice that the product is also valuable when they have reached the end of life position" - Interviewee 10

Another challenge that the interviewees raised is the high costs associated with recycling and repairing electronic products in Europe. They highlighted that the expenses incurred in recycling are a costly process in Europe. This often leads to the exportation of E-waste to developing countries where labor and operational costs are lower. However, this practice raises ethical and environmental concerns, as these countries may not have sufficient regulations or infrastructure to ensure safe and sustainable recycling practices.

"in Europe, the cost of the recycling is too much. And so if we don't do that we push in the rest of the world where they haven't they write low of the security on the working to do a work that we don't want to do" - Interviewee 2

Despite regulations in Europe that prohibit the export of E-waste to developing countries, interviewees highlighted the exportation of E-waste to developing countries which sometimes is possible if they export it for "reuse" purpose.

> "And I also think that some products are brought out of the country for reuse, but those are also never reported" - Interviewee 9

> "I think the only problem that is regarding export is when you export it as a product and not as waste. You say this is reusable products and then you have no control, it can go wherever. And that's, I think, what we can see in these dump sites in developing countries" - Interviewee 5

Moreover, the interviewees highlighted the presence of unofficial channels for the collection of E-waste as another challenge in the current system. According to interviewee 10, retailers often resort to unofficial methods of collecting E-waste from professional users if it is more advantageous for them, which operates outside the official supply chain and lacks efficiency. This observation was supported by interviewee 9, who noted that only 60 percent of E-waste is collected through official channels

> *"If this chain is not a producer in the EPR way, then they are not allowed actually to have to take back obsolete product or live product from the end user. Yeah, they can take them back as a service, but they have to deliver them to the producers or to some of the collective schemes.[...] But if they investigate and find out that they can earn a lot of money by taking those products, they have taken back from the customers the absolute product, and they could sell them, or they can sell them as used product, or they can sell them to some recovery companies, then they could be tempted to do it [...] And then we will never have the figures and the amount of end of life product will not follow the normal channels. So that's an example of unefficient and not part of the system supply chain"* - Interviewee 10

> *"It's 60 somewhere percent. But that's I guess collected through official channels because I do think that a lot of the waste is collected through channels that aren't the correct legal ones."* - Interviewee 9

The interviewees highlighted concerns regarding the lack of digitalized business processes of existing incumbents in the E-waste management sector. Interviewee 3 emphasized the issues of transparency and operational inefficiency among recyclers due to the traditional

way of doing business. Interviewee 6 agreed with the point and mentioned that E-waste management is a complex process due to the involvement of multiple stakeholders. However, the adoption of integrated digital solutions could help address these challenges.

> *"And currently a lot of recycling centers are working with telephone or with fax. So very traditional solutions and they have a lack of transparency. How many orders are there? Any special elements about it? And with us they increase a lot. They get an increasement of efficiency because it's very easy to do containers full. I click on empty it and the order is sent out and they increase the transparency within the process"* - Interviewee 3

> *"Simple business model in linear way but now it's complex business model and multi-actors are involved in doing circular of buisness, therefore using intergrated software is necessary otherwise one application like ERP is not cant process it"* - Interviewee 6

6.2.2.2.1. Quality Control

The subtheme "quality control" explains the importance of strict measures to ensure effective control and monitoring within the E-waste management system. This includes mechanisms such as verifying and cross-checking reports provided by producers and collection schemes and forcing producers to register with the DPA system.

According to Interviewee 10, monitoring and control of reports and data about the quantities of EEE put into the market by producers, as well as the amounts collected, reused, and recycled, is carried out by Environmental Protection Agency (EPA) authorities in Denmark. However, the interviewee highlighted concerns regarding the efficiency and effectiveness of this monitoring system. There may be limitations or challenges in ensuring accurate and comprehensive reporting, impacting the overall transparency and reliability of the data provided.

> *"[...] Naturally I would say so that when it comes to the put on market values, we are doing an auditor statement for the biggest company. So they have to have an independent auditor to make a statement that the figures are okay. So they are controlled that way around for the take back for the collection amounts. Well, it's a little bit different because they are in reality they are not detailed controlled. It is not DPA but the authorities that ENS EPR which is responsible for making contact*

visits and controls within those companies to make sure that the figures are correct" - Interviewee 10

"But I think that we have to admit that it's not an super efficient control system which has been established here" - Interviewee 10

Interviewees 9 and 10 asserted that enforcement is needed to control the free riders not registered with the DPA system in Denmark and EPA system in Sweeden and are selling the EEE through online platforms without taking responsibility for taking back the E-waste.

"And we must admit that since 2006 it has been the same story year after year. No, actually enforcement is done by the authorities. So that's also why we're having we don't know the exact amount, but we have a lot of free riders in this system. But also we are having uncertainties in the data supply, naturally, because if people or if companies are not registered, we will not receive the data" - Interviewee 10

"[...] And I think that there needs to be a lot more enforcement from the Swedish EPA to find these separate flows and also to find the free riders of producers who put electronics on the Swedish market but that don't report it because I also think that's a very big issue, especially from foreign companies selling through e-platforms. I think that there's a lot of unreported electronics that come through these ways and I guess the answer of why it can exist is that the enforcement isn't enough" - Interviewee 9

6.2.2.2.2. Policy Limitation

The "policy limitation" subtheme explains the challenges that policy imposed for the exiting procedures of incumbents.

Interviewees 9 and 2 mentioned that E-waste regulations are different in each country, which makes it difficult to implement properly. Following different regulation in each country make it difficult for producers to adopt with it. This way, producers will follow the regulation also in the small markets.

"Yes, so I think there are a couple of issues and I think our main concern is that it comes from an EU directive. But the legislation looks different in every country. And I think that if you want to really impact or have an impact on the large producers, you need to make regulations that are the same within the EU. And that

also makes it more, I guess, easier for the producers to follow the regulations because they're the same in each country, whereas now you have different regulation in each country. And it's quite difficult, I think, for companies that sell to many markets in Europe to keep track of all of these different laws in the different countries" - Interviewee 9

"They must introduce regular mentation in every country with the same approach. Because if in Italy we could do. Energy with the carbon in Sweden is fake because you haven't the same goals. For the waste is the same. We need the KPI or index to represent it" - Interviewee 3

A technology solution provider agreed with the point mentioned earlier. The interviewee emphasized that variations in policies across different countries make developing uniform and integrated digital solutions difficult. These policy differences can create barriers to developing and implementing standardized technology solutions for E-waste management practices.

"I suppose compliant, the waste regulations do occasionally change, so of course we have to keep abreast with all of that. It's really important for us to be in contact and get feedback and speak to our clients, because we're software developers and they're the ones that are actually running the waste management businesses" - Interviewee 2

The interviewees mentioned another limitation of existing policies in terms of their lack of restrictiveness and complexity, which hinder transparency in E-waste management. The interviewees expressed difficulties in understanding the specific producers or companies responsible for generating different types of E-waste and the corresponding quantities.

"And also it could better because there's also some legislation that kind of prohibits this transparency, especially when it comes to private companies on how much waste they're producing and what kind of waste they're producing" - Interviewee 7

"And also it could better because there's also some legislation that kind of prohibits this transparency, especially when it comes to private companies on how much waste they're producing and what kind of waste they're producing" - Interviewee 3

6.2.2.2.3. Need for Policy

The subtheme of "need for policy" highlights the existing challenges and limitations within the incumbent business processes in E-waste management, emphasizing the necessity for new policy interventions.

Interviewees 10 and 7 emphasized the importance of legislation in facilitating effective monitoring of E-waste management. They emphasized the need for regulations to compel companies to share environmental activity data, enabling better oversight of their practices. Additionally, the interviewee mentioned the importance of introducing new regulations to mandate collection schemes to monitor the reports of producers about E-waste collection, reuse, and recycling. Multiple control layers, including government authority oversight, can be established by implementing these measures to ensure transparency and accountability in E-waste management practices.

> *"What is actually coming up now in new legislation is that not some of the collective schemes are forced to make self control system or paradigms for doing that. So they have to make their own controls, they have to document the controls and sometimes from time to time the authorities will ask for the controls to look after if it's correct"* - Interviewee 10

> *"There needs to be a national legislation or international legislation that dictates that there are some minimum standards of what data should be provided. So even if a company I think if a company is not willing to share data, you should find another one because what is the reason? And the reason might be that they're hiding something or they're doing something bad."* - Interviewee 7

The interviewee also suggested that regulatory measures should be implemented to encourage and support integrating digital solutions into E-waste management.

> *"I think it can be difficult to have this piggy tail technology if you don't know who should start, who should invite to develop this. Kind of difficult to figure out. So that's why it might be necessary with some legislation to kind of have it started because maybe it can happen by itself"* - Interviewee 5

6.2.3. Role of DTs in Operational Efficiency

The theme "operational efficiency" explains digital technologies' role in enhancing E-waste management processes' efficiency. This includes various aspects such as task automation,

real-time waste monitoring, optimization of logistics and transportation, and compliance with regulations through unified reporting.

Digital technologies have not been used broadly in the E-waste management sectors. Interviewee 2 said, “technology not used broadly”. Interviewee 3 agreed with the point and mentioned that using cloud solutions and mobile applications for business operation efficiency is a big step for waste management actors right now.

> *“They come to us with paper based solutions and then they work with a cloud based solution with mobile applications. And so they do already a very big step and they will need more time until using further technology. So for them at the moment there is not the business case”* - Interviewee 3

However, the digital solution provider companies talked about the potential of DTs in the operational efficiency of waste management, including automation of tasks, better reporting, unified data, transparency, and better decision-making based on real-time data. Interviewee 4 mentioned that DTs can be used to “organize trucks and vehicles, cars, vans. It can be helped to monitor orders that come in and go out. It can be helped to organize plans for drivers to utilize containers. And also it can be used to help manage accounts, the accounting team as well when it comes to paying invoices”. Therefore, the waste carrier and waste processors can have a better insight into their business processes by adopting DTs. Because their DTs solution is integrated with business intelligence tools, unlike the manual process like working with Excel files provide E-waste management companies with unified reports from different aspects of their business. With these analytic tools, they can make proactive decisions about their business. Also, they can clearly understand the amount of E-waste collected, processed, and disposed of in the landfill.

> *“Okay, so we're integrated with Tableau, which is a business intelligence tool, and we have lots of standard reports in the system as well. So imagine if you're operating a business and operationally, there's lots of services and everything happening every day, but unless you can actually analyze what's happening, you can't obviously it's difficult then to make data driven improvements. So with the analytics tool, we're essentially showing our customers monitoring all of their KPIs in real time”* - Interviewee 4

> *“waste carriers and the people that process waste. You know, that's our typical client. So, you know, digital transformation for those businesses is enabling them to*

be able to actually glean the insights about their business, to more proactively, make decisions, understand the numbers in the business better. [...] hopefully it's helping our clients make better decisions so that they can monitor exactly how much of their waste that they're collecting is diverted from landfill, exactly what's happening to it" - Interviewee 4

The advantages of digital technologies for E-waste management were highlighted by the interviewees, including improved accuracy, transparency, data availability, efficiency, and enhanced reporting capabilities. Interviewees 3 and 8 specifically emphasized that digital technologies can enhance transparency by providing detailed information about the inventory, such as the type and quantity of recycled waste. This transparency can facilitate better pricing strategies when selling recycled materials.

"Increase of efficiency, increase of transparency, and also to get information much earlier and to have information much better available. So one aspect of a cloud based software, wherever you are, you can be connected to your company" - Interviewee 3

"Then there is a whole data management in order to of course also technology in order to better sort the waste and find out what waste to have and then there is also something about technology to keep track of what waste to have. So in the sorting facilities that you can see now we have this amount of plastic, this amount of metal and that inventory control can help you in order to sell it at better prices and that is also improving the life of the waste figures" - Interviewee 8

"The advantage of digital technologies in waste management is the following: cost reduction, improved production, better planning, and report generation" - DS_1

Reduction in operation cost also mentioned by the interviewee. Majority participants of this study agreed to the points that DTs reduce operation costs. Interviewee 7 mentioned that "most of the companies are very willing to go into a more digital process because it can save money and it can also save them resources and it also opens up for different markets" Similar point was also mentioned in the DS_1, where it says that "By implementing this software in waste management processes, organizations experience improved collaboration, shared knowledge, and reduced operational costs".

6.2.3.1. Role of DTs in Logistics and Transportation

The subtheme "logistics and transportation" explains the role of DTs in optimizing logistics and transportation in waste management.

Interviewee 5 mentioned that, in Denmark, for collection of E-waste sensors has yet to be used. However, the interviewee mentioned that using sensors in the E-waste container to inform when it's full will optimize transportation operations better.

> *"We do a lot of testing also. And one of the testings is kind of optimizing the emptying of the bin so that you don't empty air [...] It really efficient if you look to the door to door collection, but it's more efficient if you have this kind of tubes or larger containers where you can have some sensors to tell when it's full and you have some other driving logistics"* - Interviewee 5

Interviewee 9, representing a collection scheme, agreed with the point mentioned above and further explained their current practice of using a manual booking system to manage logistics when E-waste containers reach their full capacity.

> *"Yes. So it's basically just a booking system where I guess the collection points that we have, they can book the transports when they have full cages or full containers and then yeah"* - Interviewee 9

On the other hand, Interviewees from digital solution provider companies mentioned that they have developed and implemented different approaches for waste collection and route management. Interviewee 2 mentioned that they developed a sensor like a capacitor where it understands the level of the bin in four levels. Also, the sensors can send pictures to analyze the amount and type of waste inside the bin.

> *"Develop a sensor like a capacitor where the electric is the waste to understand the four levels of full. So that challenger was solved by this approach"* - Interviewee 2

> *"The first is to photograph day waste, to understand how kind of waste we put inside. At the end of the collecting, you know that in that zone you have glasses or paper and so on"* - Interviewee 2

Interviewee 3 highlighted the utilization of DTs in their efforts to develop a collaborative solution with the government aimed at notifying waste pickers and recyclers when the collection bins reach their capacity. This approach is particularly relevant due to the individualized containers utilized by different companies.

"The second solution, we work together with local recycling centers. So they are owned by the government. So in an urban area, for example, and the people bring their material there and we start with the communication. Okay, the container is full. [...] The container is full from the recycling center to the waste management company. So for example, for one material it is one waste company, for another one, it's a different one" - Interviewee 3

Another similar approach mentioned by Interviewee 4, she mentioned that while collecting the bins from the collection points, they keep records of the bins' underweight, which helps to select the optimum time to collect the bins next time.

"I suppose from that you could pick up some analytics on maybe we're going to go and service a particular bin. But actually what we've noticed is that every time we're servicing it's underweight, it's not at its like max weight if you like, which would be the optimum time to collect it" - Interviewee 4

6.2.3.2. Role of DTs in Collaboration and Information Sharing

The interviewees emphasized the importance of collaboration among actors in the context of E-waste management, particularly for improved recycling practices and enhanced traceability of products. They highlighted that effective collaboration relies on efficient information-sharing mechanisms between the involved actors. However, it was noted that manual information-sharing processes can lead to complexities and challenges in achieving seamless collaboration.

"Yeah. So one part is of course that it's less administration because with all manual processes there's more administration and it takes more time. [...] And also I think it could definitely bring in the future better control and traceability of the recycling and the recycled material" - Interviewee 9

Information sharing between actors involved in E-waste management is both digitalized and manual. In some aspects of the business, the systems are connected through API for information sharing. Interviewee 9 said, "We have the reporting portal where our customers can enter how much they have put on the market, and we then have an API connection to the EPA to report this." However, most of the information-sharing processes are manual, where the actors exchange Excel files and Emails. As the interviewee 9 said, "a lot of the processes are still quite manual. We work a lot with Excel, for example, and email". In addition to this, there is another system in which the recyclers share their

information about treated E-waste, which is called "Reptool". This system is developed by the WEE forum.

> *"the first way is through Reptool, [...] where you can basically follow the material from when it's been brought into their facilities and then maybe it's been shredded and then fractioned into different types of material. And then those materials are sent to some other treatment partners and then are treated in another way until you receive the fully recycled material"* - Interviewee 9

Similarly, Interviewee 3 highlighted the significance of data sharing and system integration in E-waste management. The interviewee emphasized the current practice of manually recording information in each system is inefficient. Instead, there is a need for systems to communicate and share data seamlessly through API.

> *"At the moment within that chain, very often the same information is manually written down in each system. So the systems do not collaborate. There is so far not that communication standard to work together between the system"* - Interviewee 3

However, Interviewee 6 and Data Source 1, representing a digital solution provider company, emphasized developing and implementing integrated software solutions in waste management companies. They highlighted that these solutions have improved collaboration both internally and externally. Internally, the integrated software integrates various business functions, enabling access to unified and real-time data across the organization. Externally, the system facilitates collaboration between different actors involved in E-waste management, such as producers, collection schemes, and recyclers.

> *"In terms of collaboration, digital technologies have enabled collaboration within waste management operations, both internally and externally. Internally, the implementation of advanced solutions like ISB Global's waste management software enables seamless integration of data from various business functions. This integration of real-time data empowers decision-makers with improved insights, leading to more informed choices and streamlined report-generation processes. Externally, digital technologies have fostered enhanced communication and information exchange among stakeholders, including brokers, logistics providers, and reprocessing companies. This has facilitated smoother and more transparent transactions, promoting seamless interactions and efficient coordination within the supply loop"* - DS_1

"So responsible design and production and extended producer responsibility EPR are two of the same things, but different processes in one application to manage where the materials come from, trace the material, and then have it ticked off according to sustainability goals" - Interviewee 6

Interviewees 1 and 7 highlighted the potential of blockchain technology in facilitating information sharing among various stakeholders. They emphasized that blockchain technology offers a transparent platform where stakeholders can share and access information about the entire lifecycle of a product. This includes the product's origin, storage locations, and composition. By utilizing blockchain technology, stakeholders can enhance visibility and traceability throughout the supply chain, enabling better understanding and monitoring of the product's journey from production to disposal.

"But there also needs to be a system for this to be efficiently shared in between the different stakeholders. I think it's maybe a little bit in the future, but I think the whole blockchain technology could really help with these different things with the traceability in the data and the value chains for the different companies" - Interviewee 7

"Furthermore, we see that more and more products get these passports, so to speak, where you see what is in this product, what it consists of and where has it been stored. Like a ledger saying when you buy this computer you find that there are plastic source from this company which is sourced and it's wrong to come over here. So you get this total map out of what is in a product and where it's come from and how you should get rid of it at end of life. So you know that okay you need to take these part away from each other because this plastic has plastic recycling and this material has good to this and so forth" - Interviewee 1

Interviewee 6 mentioned that the current sectors of waste management lack integrated systems, emphasizing the need for such integration. He further discussed an integrated software solution for waste management developed by a software solution provider company. According to the interviewee, the integrated software solution combines knowledge from various business process of waste management such as logistics, transportation and SAP (an ERP software solution) to create an integrated software solution that can be utilized anywhere in the waste management and recycling supply chain. The interviewee emphasized that their integrated software solution enables effective

tracking of materials from production to recycling, thereby enhancing transparency and traceability within the process.

> *"And this has come out of the logistics experience that we have, transport experience that we have, SAP experience that we have, the industry experience that we have in waste and recycling. And so as time has progressed in [company name] and we've entered into a different material stream, for example, we've learned a lot and put that into the software solution"* - Interviewee 6

> *"But what we have is a leading technical solution and an industry specialist solution which can sit anywhere in the supply chain and manage waste and recycling, the movement of materials and the traceability of those materials downstream into recycling, and the actual manufacturing processes for recycling and Intersecondary markets as well"* - Interviewee 6

6.2.4. Resistance to Change

The "resistance to change" theme encompasses the various forms of resistance encountered in the transition towards a CE in E-waste management. This resistance includes a reluctance to adopt digital technologies for improved transparency and efficiency, adherence to traditional business practices, and challenges associated with implementing CE strategies.

The interviewees expressed that companies in the E-waste management sector have become accustomed to operating businesses in traditional ways, which have been established and followed for several years. As a result, there is a notable reluctance among these companies when it comes to embracing changes and adopting CE business models and strategies.

> *"The main challenge is that for your customer who will have to purchase this new business model. It's a very conservative industry, they've done it the same way for hundreds of years, I will almost say. So they might not be as keen to change it"* - Interviewee 1

Interviewee 4 had similar ideas; she mentioned that waste management companies are used to traditional business and unwilling to adopt digital technologies.

"[...] We still come across prospective clients who are fully on paper" - Interviewee 4

According to interviewee 10, while some producer companies have digitalized systems, they are reluctant to connect their systems for data sharing. Additionally, the interviewee highlighted challenges in collecting data from certain collection schemes, indicating potential limitations in data availability and accessibility.

"Yeah, I think we should first take the producers. Normally, they are in a position where they have a certain and sometimes very high level of digitalization in their own systems. But very few of them have actually said that they would connect system to system, for instance, with DPA in transferring data" - Interviewee 10

"And that goes actually also for the collective schemes. Some of them, the smallest of them are not sending files with the figures but they're actually digging in by their keyboards the annual reporting that's also a little bit different. Difficult to understand how that is possible, not to go up a little further in the digital chain" - Interviewee 10

According to interviewee 10, using RFID tags or barcodes could enhance the tracking and management of E-waste throughout the supply chain. However, the adoption of such technology by producers is limited, with cost mentioned as a reason. The interviewee argues that this explanation is questionable, as RFID tags are affordable. The resistance to adopting RFID tags and sharing data is attributed, in part, to the existence of unofficial channels within the industry that benefit from limited transparency and oversight.

"For instance, why are we not using RFID tag or Barcodes or whatever to track all the waste out from the municipality in the whole supply chain until it was treated? Why is that possible now after some years? [...] Oh it's most too expensive they said very expensive [...] but actually I'm not sure I can understand it, because when I'm going to the supermarket buying a bag of potatoes and for ten Danish crowns, it's very little and they have put on barcodes and everything, and they can track that certain bag of potatoes back to actually where it was digged out of the soil" - Interviewee 10

"I think that unofficial lines as you described before is a very interesting playing field for some of the actors. So they don't like so much control so they have just

argued that oh it's so expensive but I think that it is the level of control that they don't support" - Interviewee 10

6.2.5. Niche

The following section presents themes that enlighten new practices or technologies contributing to the improved recycling of E-waste or alternative approaches aimed at E-waste reduction and better management.

6.2.5.1. Strategies for Reduction of E-Waste

The theme "strategies for reduction of E-waste" explains the strategies, such as the reuse, modular design, product services system, and refurbishment that companies adopted or are willing to adopt for the reduction of E-waste.

The interviewees emphasized the significance of reuse as a more viable approach for extracting value from E-waste compared to recycling. They highlighted the importance of collaboration among various actors involved in E-waste management, such as collection schemes, producers, and re-use partners. By working together, these actors can facilitate the refurbishment, repair, and redistribution of electronic devices, extending their lifespan and reducing the need for resource-intensive recycling processes.

"I think that everything that we do is part of the circular economy. But I think that we could definitely better at, for example, reusing more products instead of recycling them" - Interviewee 9

"El Retour, has actually established two centers of reuse here in Denmark and they will try to actually pull out more and more product for reuse. So this is maybe also a start of circular economy if they can have a cooperation with the original producer of the stuff" - Interviewee 10

According to Interviewee 10, a significant number of reusable products can be identified within the E-waste stream. Additionally, he emphasized that adopting a reuse approach is gaining momentum, particularly among small companies that demonstrate ambition in exploring new and sustainable business models.

> *"[...] I don't know the business model, how is the level of cost in doing that but I think they would be able to find a lot more product which could be reused in reality"* - Interviewee 10

> *"product is actually pulled out of the waste stream and having a second life. But the business model are driven by mostly small companies, more idealistic people who is actually making up maybe a good small business for themselves"* - Interviewee 10

The interviewee highlighted the importance of modular design as a solution to enhance repairability and facilitate the refurbishment and recycling processes of EEE. By designing EEE products with modular components, it becomes easier to replace or repair specific parts rather than replace the entire device.

> *"So I think we have to go in a way where we have more transparency on goods material that we are sourcing but also that we are designing products to be refurbished and repaired and also to actually give repair manuals and also to sell spare parts for components"* - Interviewee 7

The interviewees emphasized adopting a product-service system as a more sustainable approach to waste reduction. According to the interviewee, this model encourages producers to design products with longevity in mind, as they are responsible for maintaining and repairing the products throughout their lifecycle. Additionally, the interviewee highlighted the financial benefits of this model, noting that adopters of the product-service system pay for the use of the product through a monthly fee based on the services provided. This approach can lead to improved cash flow for the firms.

> *"furthermore, you will have an element of better controlling your cost because now you know each month how much cost it's going to be and know that it's limited because all the risk is covered by the guarantee from your company. So there's a cost element and there's a sustainability element of it. And then of course"* - Interviewee 1

> *"Instead of paying 1 million upfront, they will pay it in small installments over a larger period and they will actually make sure that they have cash for a longer time and it will be easier for them to budget, like downtown sorry, on the machine.*

Because they will know that Eurocon is in the responsibility to maintain it and they don't have to pay additional fees each time it breaks down" - Interviewee 1

6.2.5.2. Potential of DTs in Enabling CE Practices

The main theme, "Potential of digital technologies in enabling CE practices," explores the positive influence of digital technologies on E-waste management. This theme focuses on the potential benefits and advantages that digital technologies offer in enhancing different aspects of E-waste management, such as reuse, modular design, and product tracking through the lifecycle for better recycling of E-waste.

Most interviewees agreed on digital technologies' potential to provide comprehensive product information throughout the entire life cycle. The availability of such information was identified as a key factor contributing to various aspects of E-waste management, including maintenance, collection, separation, and recycling.

Interviewee 10 mentioned that "several circles in the life of a product, and I think that digital development could support that". Interviewee 2 also stressed the importance of information about the components of products by mentioning, " [...] the future of the waste is to have the information of the waste directly to the object that you buy in the supermarket".

In addition, the concept of digital passports for products was mentioned multiple times by the participants of this research. Interviewee 5 said, "And I think we have some of these digital passports in the EU system. And maybe there's also something coming up for electronics". Interviewee 1 agreed with this point; he mentioned, "I think the digitalization will assist in creating these passports of materials. I think that's where we can make sure that we get all that information and all the data we need to form further uses of further partners down the lifecycle". Furtherly, he mentioned that this information is helpful for the other actors such recyclers to recycle better the products if needed "As I said before, we need systems that can digitalize building what's inside them and make them available to other recyclers so they know that they can actually contact your company to figure out to get those exact windows or that material they need for the building, maybe just down the street".

Moreover, one interviewee mentioned that DTs have been used poorly in data management of E-waste, but for physical management, it has been used much more poorly. The interviewee emphasized that digital technologies possess the potential not only to enhance administrative aspects such as transparency and data management of E-waste but also to enable more effective physical handling of E-waste. For instance, the interviewee suggested exploring alternative collection methods, such as direct collection from individuals, and leveraging digital technologies to track better and collect E-waste within a circular model. The participant emphasized the importance of digital technologies to optimize both the data management and physical (collection and separation) methods.

> *"We are very old as I just described in our data handling in some areas, but even more old fashioned in how we treating the product physically. I think that the next step could actually be to create system which will support a better physical handling. [...] But if you can do that in such a system, you can also do it with high valuable electronics. In future you have to find the new digital solution to bring the end user together with a new user so that you will have this more than one circle"* - Interviewee 10

Interviewees 1 and 3 furtherly mentioned that a digital passport for products would allow the recyclers to have enough information about the components of the products, which will be helpful for the recyclers to classify and recycle the E-waste better. Interviewee 9 mentioned that the classification of E-waste is complicated because it has been done manually since now.

> *"Yes, so I think that the digital product passports, they haven't been launched completely yet, but they're at least in progress I guess. I think those will definitely help the waste management to better separate products into different categories for the recycling and that this can be done because now a lot of the separation is done manually"* - Interviewee 9

> *"product path. You know that concept. Yes. So this will make it easier for waste management companies to know, okay, what is inside or what materials are inside and which ones can be reused or recycled, in which ways this can also help to control"* - Interviewee 3

> *"And I think also when we get to Waste Election and Waste Management, they would need to know what are they receiving and how can they dismantle a product*

and what does it consist of. Imagine if you were to tear down a building and if you knew on forehand what it consists of, then it would be easy for you to make contracts with partners and demolishing companies" - Interviewee 1

Furthermore, Interviewee 7 highlighted the role of digital platforms in enhancing the relationship between producers and consumers, thereby enabling alternative business models. This includes options such as leasing or loaning products instead of traditional purchasing. By utilizing digital platforms, producers are able to track the materials and products throughout their lifecycle, providing a higher level of transparency and accountability.

"So I think there are many places where digitalization can find its way also to make it more convenient. Also for consumers to loan products instead of, for instance, buying products that's also like digital platforms needs to be easy for consumers" - Interviewee 7

"Also, there are so many different aspects [...] For instance, they might also be able to track okay, if the product is sold to a consumer track or have a relationship with the consumer on repair. And also if the consumer doesn't want the product anymore, the end of the product's life, they can give it back to the producer. That can be enabled by digital technologies." - Interviewee 7

6.2.5.3. Role of DTs in Raising Consumer Awareness

The subtheme "role of DTs in raising consumer awareness" describes the utilization and potential of DTs in raising consumer awareness regarding the composition of materials, the sustainability of products, and proper recycling practices. These technologies have been employed or proposed as tools to share information and educate consumers to promote sustainable consumption and behavior.

All of the interviewees mentioned that digital product passports and barcodes have the potential to provide information to raise awareness of the consumers about the material of product which is made of and how to recycle it properly. Interviewee 9 said that *"I also think that the digital product passports can help here where consumers can see both, I guess, what the products contain but also how to recycle them properly and yeah, they could also be given an indication of if the product is good from an environmental point of view or not. So I think that's definitely something that can help both with not only with recycling but also from a consumer point".* In support of this point, interviewees 2 and 5

noted that using the barcode is necessary for providing information to the citizen or other actors involved in waste management about the products' composition and methods for recycling. Also, the price of the barcode will be less than the ink of the printer to print information on the package of products.

> *"[...] why the barcode not upgrade? Because the cost of the barcode now. Is the ink to print it. In the future, if you want to do RFID or other, the cost is ten or 1000 of the print"* - Interviewee 2

> *"Then you're about to develop some other information tools where you can kind of scan the barcode of a product and then figure out how to handle it as a waste item and this kind of programs"* - Interviewee 5

Additionally, interviewee 2 asserted that some mobile applications have already been developed to provide information about the product's material and how to recycle it by scanning the barcode. He mentioned that improperly recycling waste might be a simple error for the consumer, but its impact is enormous on the industry. Therefore, consumer collaboration is necessary.

> *"There are some app now that you photograph the barcode or the object and say to you where do you put [...] This is a big value because now, for example, we put something in the paper that we must put in the differential waste or something in the plastic that we put in the paper. So for you [consumer]this is simply error. But the impact of the industry of the recycling to manage a small part of another waste inside is a big problem. So the citizen has conceptability or know how and where put the right object in the right box. And this changed the mentality to understand"* - Interviewee 2

Interviewee 8 had a similar idea, and he mentioned that DTs could be used for spreading information to raise public awareness about sustainability problems in different countries.

> *"But I hope that because you can spread information, maybe that is the most important. So everyone can see the problems that you have with waste management in different places of the world. You can see the consequences of plastic and the waters on the land in many areas of the world. And I hope that the fact that you can see the consequences of what you do can also contribute to change behaviors"* - Interviewee 8

Interviewee 2 added to this information by mentioning that information from the bins transmitted by the sensors is not only useful for waste management but also for consumers. He asserted that this information could be used to inform the consumer about the nearest empty bins to dispose of their waste.

> "Now who do some sensor for the bin but the real value is not the sensor it's the application that you can give in an app to your citizen. And when you go out you say I needed to collect to the box the glasses and the applications say to. You where is the emptiest box of the glasses? Near you. So the approach of the technology is not only a tool in the end of the waste management company is also a tool in the hand of the citizen" - Interviewee 2

In addition to raising awareness of consumers by DTs interviewee 8 mentioned that, they have used mobile applications to educate the waste pickers not only how to collect and sort the waste but also teaching daily life skills like how to save money by teaching basic of mathematic.

> *"And then you have across the whole apps and mobile technologies in order to train and educate person training and educating how you use the technologies for the waste pickers for the sorting, how the sorting you can say business is run, but also training the waste pickers in their personal life to better control their, for example, their finances through learning of mathematics"* - Interviewee 8

6.2.5.4. Barriers to Digital Technologies

The main theme "barriers of digital technologies" encompasses the various limitations and challenges associated with the adoption and implementation of DTs within the context of E-waste management. This theme sheds light on the barriers that hinder the widespread utilization and acceptance of DTs by actors involved in E-waste management processes.

6.2.5.4.1. Limitation of Digital Technologies

The subtheme "Limitation of digital technologies" delves into the challenges and limitations associated with the use of digital technologies in the context of E-waste management. This theme explores the potential problems and drawbacks that arise when implementing digital technologies in the sector.

Interviewee 10 highlighted the insufficient maturity of specific digital technology solutions to meet the comprehensive requirements and criteria of the business processes in the E-waste management sector. The interviewee provided an example of a digital solution for logistics, stating that existing systems do not easily integrate with all the other criteria used in allocation. This point was confirmed by interviewee 3, who said, “Of course, there are sometimes situations where what they need does not fit to what we have. So our solution is not matching totally to what they need”. Another challenge or limitation mentioned by the interviewee is data security and privacy. It was emphasized that while developing digital technology solutions, it is essential to maintain the purpose, ownership, security, and privacy of data to prevent unauthorized sales or misuse of private data.

> *“obviously there is something with data security. When we have data on different actors, how is it managed and who's responsible? And also is it used for something good? Like we know that a lot of data, most of the data that we have on the internet is being sold to different people who are using it to sell different goods. So obviously there is an aspect of that the data should be secured and not used for financial benefits”* - Interviewee 7

> *“I think cost, of course, is a challenge. I think cybersecurity is a challenge. I think privacy is a challenge”* - Interviewee 8

Another limitation highlighted by the interviewee pertains to the high battery consumption of the sensors used in waste bins and their low resistance in rainy and snowy weather conditions. The interviewee mentioned that during snowy or rainy periods, the capacitors in the sensors do not function properly.

> *“But after three or two years we had a problem with the capacitor. Because after sometimes when the aging takes the capacitor, when snow, rain or foggy the capacitor, so the sensor don't work very wel”* - Interviewee 2

> *“The other challenge was the battery consumption of the sensor. Because we need a product who live on the street five years, six years, seven years”* - Interviewee 2

The interviewee also identified false reports generated by algorithms as a limitation in E-waste management. The interviewee expressed concerns that relying solely on algorithms could lead to inaccurate reports, highlighting the need for careful consideration and verification of the algorithmic outputs.

> *"An algorithm could do a big problem in the waste management [or] circular economy, okay, for example, [...] in general to leave the power, the decision all to the technology"* - Interviewee 2

Furthermore, an additional limitation identified is the increased cost associated with the lack of integrated software solutions. Data source 1 highlights that utilizing isolated software systems can lead to higher expenses, as more employees are occupied with managing these non-integrated software solutions.

> "Isloated software are more costly, more employee will be busy administrting the not integreated softwares. In a result, it will add more cost and burden to the companies" - DS_1

The interviewees mentioned the high cost of DTs numerous times as a challenge. Interviewee 2 said, "So the technology in the waste management is a cost. In this moment too much because every object must be with battery. Power and the battery hour is a big cost". Interviewee 9 agreed and noted that "but it's also an issue of cost on our end, how much we can develop our digital technologies because, yes, it might make things more efficient, but it's also a cost that we need to take when developing these digital technologies".

6.2.5.4.2. Digital Technologies Implementation Challenges

This subtheme explains the challenges that digital solution providers face while implementing digital solutions for waste management companies.

Interviewee 4 highlighted the dynamic nature of E-waste regulations, emphasizing that they undergo regular changes. As a result, waste management companies face the challenge of adapting their business processes accordingly. This aspect poses challenges for digital technology solution providers, who must stay updated to ensure their solutions align with the evolving regulatory landscape.

> *"Well, I suppose compliant, the waste regulations do occasionally change, so of course we have to keep abreast with all of that"* - Interviewee 4

Furthermore, interviewee 8 highlighted that apart from cost, data security, and privacy concerns, technology maturity, infrastructure availability, and the prevailing culture of

technology adoption can also pose significant barriers. These challenges may be more pronounced in developing countries compared to developed countries.

> *"I think cost, of course, is a challenge. I think cybersecurity is a challenge. I think privacy is a challenge. But apart from that, I think it also depends very much on the digital maturity in the different countries and even the different cultures. You can say in different companies. I see Denmark as a pretty digitalized country"* - Interviewee 8

This point of digital maturity and the existence of demand for adopting DTs in developed countries was confirmed by interviewee 6, who said: "challenges initially was market, technology maturity, project management but now they [are] solve [d]."

Another interviewee mentioned that the partners in the E-waste management sectors are not digitilized, so it can create a challenge for the companies that are willing to adopt DTs. Interviewee 9 said, " I think, yes, in some ways it's due to the partners". This participant furtherly mentioned that firms are not aware of DTs solutions and they are late adopters.

> *"but I think that we're probably not aware of all things that we could do [...]. Also, I think in general, the industry is, I guess, quite late adapters of new digital technologies"* - Interviewee 9

This point of late adopting DTs confirmed by the interviewee 3, who said that "I think a lot of companies don't find the time to think about, okay, is there something which might help us in our processes? Because they are so overloaded with their daily business". Interviewee 3 also mentioned that in some firms old mindset hinders them from adopting DTs, where the interviewee said, "So I think that barriers for a company to go into a digital world, we just think it's because the companies maybe has a little bit of an old mindset". He supported this point by mentioning that "that only 30% of the waste management companies are digital ready".

Lack of technical skills" is another concern raised by interviewees regarding the challenges faced by E-waste management companies in adopting digital technologies due to insufficient technical skills among their employees.

Interviewee 3 highlighted the lack of technical skills among employees in waste management firms, which can sometimes pose challenges for adopting digital technologies

due to the difficulties associated with managing such changes. The interviewee further noted that since they are in direct contact with clients, it is a significant learning process for employees to adapt to and utilize new tools and technologies.

> *"They have a digitalization rate and experience, which is really the bottom line [...] They are afraid if they can manage the change with their people because the employees are far more away from digitalization"* - Interviewee 3

Interviewee 4 mentioned that "I would say it's getting easier for them. When we started this 16 years ago or whatever, it wasn't so easy for them then [...] But I would say now that even in sort of, you could say quite an old fashioned industry, they do all understand the importance of undergoing that digital transformation and they're much more aware of the benefits that it can provide. So I would say it's certainly getting easier and easier all the time". Similarly, Interviewee 2 acknowledged a lack of technical skills among employees, but the interviewee also noted that people are getting familiar with how to use DTs due to technology development and the usage of smartphones by people. The interviewee suggested that organizations can encourage employees to embrace digital technologies, emphasizing that technology is intended to optimize their work, not replace them

> *"Fortunately everyone use smartphone and so on, so the transaction is going at the best. The main constraint is to push your employees to use for working that technology [...] you must explain [technology] are optimizing their working, not [overtaking]"* - Interviewee 2

6.3. Summary of Findings

The following table is the summarized version of the finding illustrated before.

Main themes	Key findings
Climate change	Climate change acts as a driver for the transition towards sustainability and CE. Sustainability issues like scarcity of raw materials, and climate change pressure regimes to reconsider their existing practices and adopt sustainable business models. In addition, sustainability is a value proposition for firms to enhance brand reputation due to market demand.
Social awareness	Social awareness has increased recently with the growing demand for green products. In the context of E-waste management, people

	are aware of the proper disposal of their waste. However, despite being aware, everyone is not taking action. For instance, people are not returning their small devices (smartphones, laptops) when it's reached their end of life to the designated collection points. This is due to a lack of knowledge about the financial benefits of E-waste for recycling and reuse. Bridging this knowledge gap where DTs can play a role in raising awareness of people. In addition, SMEs show a greater tendency to adopt sustainable business models. Firms and governments are supporting sustainability and the adoption of CE. In the context of E-waste management, collection schemes organized marketing to educate people about the importance and proper E-waste recycling. Government in Demark, raising awareness of people about proper recycling of waste in kindergartens, schools, and events.
Policy	EPR is a driving force for firms to adopt CE practices by shifting the responsibility of managing E-waste from municipalities to the producers. Implementation of EPR led to the creation of new businesses to collaborate in the implementation of EPR. In addition to EPR, the introduction of digital passports and the Corporate Sustainability Reporting Directive (CSRD) has also been identified as a driver for the transition to a Circular Economy. The CSRD mandates that both large companies and SMEs report their environmental footprint, thereby fostering greater awareness of their environmental impact and promoting sustainability practices. Changes in the legal structure in Germany, have also played a role in driving the adoption of digital technologies. These policy changes have necessitated improved reporting mechanisms to ensure compliance with regulatory requirements and have prompted the implementation of digital technologies for more efficient data management and reporting.
Market demand	The adoption of CE practices among firms is gaining momentum, reflecting a growing awareness of sustainability issues. However, many companies still face challenges in determining which specific sustainable business models are most suitable for their operations and how to implement them effectively. Transparency and collaboration are key factors in successfully implementing CE practices within firms. DTs can be used for enhancing transparency and sharing data among various stakeholders. Thus, there is a market demand for adopting DTs.
Established procedures	This theme explains the current actors, their responsibility, and the method of E-waste collection. Actors are producers, EPR implementors, collection schemes, and recyclers. Producers are obligated to collect E-waste from the designated collection points based on the same amount of EEE they put on the market. Producers have to take back E-waste from professional users for free of charge.

	The collection scheme is an actor who helps producers with the collection of E-waste. EPR implementor is a non-profit organization that registers the EEE producers and allocates the amount of E-waste that producers have to collect based on the amount of EEE that tye put in the market from specific collection points.
Established procedure problems	E-waste collection method from households is not standard, which may lead to potential damage to products when consumers want to dispose of them. In addition, people are unwilling to return their small devices with sensitive data because they are concerned that small devices may get stolen with sensitive data from the collection points. Interviewees mentioned that there is a predominant focus on recycling rather than reusing E-waste, which limits the opportunities for extending product lifecycles. Also, professional users are unwilling to return the E-wast to producers due to financial gain. In Europe, the cost of recycling E-waste is high, leading to the exportation of waste to developing countries where unregulated recycling practices raise ethical and environmental concerns. This situation has also resulted in the emergence of unofficial channels for E-waste collection and exportation. Furthermore, the lack of digitalization in many incumbent business processes challenges transparency and efficient E-waste management. The implementation of EPR varies across different countries, posing challenges for digital solution providers in delivering tailored solutions for effective E-waste management. The complexity of E-waste regulations further complicates the development and implementation of appropriate digital solutions. The allocation of responsibilities among various actors involved in E-waste management is not clearly defined, leading to ambiguity and potential gaps in accountability. Additionally, the monitoring mechanisms to ensure compliance with E-waste regulations are not adequately enforced or restricted. Government officials are responsible for auditing and monitoring reports of producers to make sure producers are taking responsibility for their E-waste and complying with EPR and other sustainability regulations. However, the monitoring and auditing are not restricted, which leads to emerging of unofficial channels for collecting and treatment of E-waste and free riders in the market without registration with the DPA system. There is a need for policy to mandate the actors to share data with each other to ensure transparency and better E-waste management. Also, the collection scheme should be obligated to monitor and ensure the reports and figures of producers are correct.
Resistance to change	Producers are not intended to share their data despite being digitalized. Also, they are reluctant to use barcodes or RFID tags for tracking the EEE product through the lifecycle. The reason might be

	because the unofficial way of E-waste collection and recycling is beneficial for producers. Recyclers or E-waste management companies are reluctant to adopt DTs because they are used to the traditional of doing business.
Strategies for reduction of E-Waste	Interviewees agreed that digital passports, RFID tags, and barcodes could be used for better tracking and recycling of E-waste. Collaboration is mentioned as an essential factor for adopting CE principles such as the reuse and recycling of E-waste. E-waste reuse is gaining momentum among the stakeholders involved in E-waste management. The interviewee mentioned modular design as a promising approach for enhancing efficient E-waste repair and recycling. In addition, the product services system is a good approach for producers to reduce the E-waste generation and prolong the life of EEE products.
Potential of DTs in enabling CE practices	DTs can be used to enhance or enable CE practices. Interviewees mentioned that digital passports for products have the potential to enhance the monitoring of a product through the lifecycle and provide information about the composition of products which is helpful for consumers and recyclers. For the consumer, provide information to know if the products are sustainable, what they are made of, and how to dispose of them properly if needed. For recyclers, it helps for better reuse and recycling.
Role of DTs in raising consumer awareness	Also, DTs have the potential to raise awareness of people. For instance, digital passports and mobile applications have already been developed that provide information for the consumer on how to recycle and find the nearest empty bin for recycling E-waste. In addition, DTs can be used both for circular data management and better physical management of E-waste (collection, sorting, and dismantling). The interviewee agreed that DTs have been used poorly in data management but even poorly for physical E-waste management. DTs have the potential to create new business models like leasing and lending of products by consumers through digital platforms instead of buying. Interviewees mentioned that digital solution providers developed integrated software solutions for route management, logistics, finance, and administration of business processes. These solutions have the potential to help with planning, enhance transparency and improve internal and external collaboration. However, incumbent systems are not integrated, and manual registration or data sharing exists. Also, some of the actor's business processes are not even digitized.
Barriers to DTs	Data security and privacy issue are mentioned as a limitation of DTs which raise the concern of consumers about adopting DTs among actors involved in E-waste management. Additionally, interviewees mentioned that some digital solutions don’t meet the business requirements of firms. The high cost of batteries for sensors and

	capacitors of the bin is another limitation that was mentioned by the interviewees. Sensors also not working correctly (not transmitting data) during the rainy, snowy, and foggy weather. In addition, the interviewees mentioned that not integrated software solutions increase the business operation cost because a large number of employees is needed to manage it. Another limitation mentioned by the interviewee solely relying on algorithms which may generate inaccurate reports. Technology maturity, technology infrastructure, and culture of adopting DTs are mentioned as another barrier to the implementation of DTs which is better in developed countries. Lack of technical skills among the employees and the high cost of adopting or developing new digital solutions were other limitations mentioned by the interviewees.

Table 6.3**,** a summary of the findings

7. Discussion

In this chapter, the researcher has examined and discussed the findings presented in the previous chapter, considering the research questions, relevant literature review, and the MLP theoretical framework. The discussion is structured into three main parts, aligned with the analytical framework of MLP.

The first part (Section 7.1) focuses on external factors that impact the regime and niche in E-waste management. These factors include policy interventions, social awareness, market demand, and collaboration among various actors involved in E-waste management. The discussion in this section primarily revolves around how these factors influence the adoption of CE practices, drawing from existing literature on sustainability transitions, CE, and the MLP framework. In the second part (Section 7.2), the study delves into the challenges and limitations incumbents face in their current practices concerning E-waste management. The "resistance to change" among incumbents is also explored, utilizing insights from the MLP framework.

Finally, the third part of this chapter (Section 7.3) centers on the potential of DTs in enabling CE practices. This part discusses the role of DTs in enhancing social awareness and collaboration, their potential to improve the operational efficiency of actors engaged in E-waste management, and finally, the challenges and limitations related to the implementation of DTs.

7.1. External Factors Impact on Regime and Niche

7.1.1. Policy

This research suggests that the linear business model adopted by many organizations has led to environmental issues, including resource scarcity, rising commodity prices, and geopolitical instability (MacArthur, 2015). These challenges, driven by climate change's impact, have pressured socio-technical systems to reassess their current unsustainable practices and transition towards more sustainable approaches. This study suggests that companies need to adopt a CE model in response to resource scarcity and climate change. This notion aligns with the argument presented by Rip et al. (1998), highlighting that global trends can have significant impacts and exert pressure on both the incumbents who are involved in E-waste management and firms with innovative solutions and technologies.

The findings of this study suggest that the growing concern over climate change has forced governments to enact policies to promote sustainability and encourage the adoption of CE practices to mitigate the negative environmental impact of LE activities (Rizos & Bryhn, 2022; Shittu et al., 2021). The research reveals that such policies from Landscape act as a driving force for incumbents to reduce their emissions and embrace sustainable practices. Specifically, the European Green Deal was highlighted as an example of a policy initiative emphasizing the importance of CE in waste reduction through product services systems, reuse, and recycling, aiming to achieve net-zero greenhouse gas emissions, consistent with previous studies (Šipka, 2021). Consequently, E-waste management companies are obligated to comply with regulations that require transparency and the sharing of reports regarding their environmental impact. It is worth noting that some sustainability policies may not directly correlate with adopting DTs to enhance sustainability (Šipka, 2021). However, the findings indicate that actors involved in E-waste management have been willing to adopt DTs to comply with report sharing and transparency in recent years, an opportunity for digital solution providers to innovate new solutions for better E-waste management. To effectively transition towards a CE, it is essential to address both the reduction of material loops through measures such as modular design, reuse, remanufacturing, and repair, as well as the closing of loops through recycling (Stahel, 2016). However, the findings of this study suggest that current policies pertaining to E-waste management focus mainly on the recycling aspect. Consequently, this emphasis on recycling may help explain the high recycling rates observed in the context of E-waste management, as mentioned by Pant et al. (2020).

In addition, achieving sustainability requires a broad network and collaboration of powerful actors both in the production and consumption phase (F. W. Geels, 2018). In line with this point, the finding of this study suggests that a new policy is required to obligate both large companies and SMEs to adopt sustainable practices. In this regard, sustainability experts interviewed for this research were hopeful about the policy such as Digital Product Passport and Corporate Sustainability Reporting Directive (CSRD), which are not in the palace until now. The first will oblige the producers of EEE to use digital product passports, allowing information sharing about the product through the lifecycle that will enhance the product design, enhance the lifetime and help with reuse and recycling (*Digital Product Passport*, 2023). The latter forces large SMEs to report their footprints and sustainability practices to the users (*Corporate Sustainability Reporting*, n.d.). The

results indicate that these two regulations will enhance actors' collaboration and facilitate the transition towards CE.

In the domain of E-waste management, EPR represents a policy framework that imposes responsibility on producers of EEE to manage their products at the end of their life cycle. EPR policies also emphasize the importance of designing products with prolonged lifespans (Barapatre & Rastogi, 2022). This research contributes novel insights by highlighting the emergence of new businesses and actors like collection schemes and implementors of EPR due to EPR policy to collaborate with the government and producers to manage E-waste effectively. In line with prior research (Barapatre & Rastogi, 2022), the findings of this study further demonstrate the positive impact of EPR policies on enhancing waste management practices, particularly recycling. However, implementing these policies also presents challenges for incumbent firms in adopting CE practices and for niche actors in innovating new solutions, particularly for digital solution providers. Consistent with the findings of Rizos and Bryhn (2022), this study reveals that the implementation of EPR varies across countries, making it difficult for producers to navigate and comply with the differing regulations, especially in smaller markets. This inconsistency in implementation methods also hinders the ability of niche actors to develop unified and integrated digital solutions. Furthermore, in alignment with previous studies (Cheshmeh et al., 2023; Rizos & Bryhn, 2022), the allocation of responsibilities among the actors involved in E-waste management is ambiguous within the EPR framework, leading to a lack of collaboration for adopting CE and inadequate enforcement and monitoring of producer obligations, which ultimately hampers transparency efforts.

7.1.2. Social Awareness

The findings of this study, consistent with prior research (Islam et al., 2021; Wieser & Tröger, 2018), highlight the significance of consumer awareness in adopting CE business models. Moreover, the study identifies an increasing demand for environmentally friendly products, particularly among the younger generation, which pressures firms to embrace sustainability and CE practices in order to meet the consumer's demand. In the context of E-waste, people play a crucial role in promoting reuse, remanufacturing, and recycling (Ottoni et al., 2020b). However, this research in line with Rizos & Bryhn (2022) study, reveals a lack of social awareness regarding the financial benefits (making new products out of recycled materials) of E-waste and the reduction of the environmental negative

impact of it through proper reuse and recycling. Consequently, people exhibit reluctance to return their E-waste for recycling, particularly small devices that can be kept at house easily, posing challenges to adopting CE principles in E-waste management. This point support F. W. Geels (2002) perspective that social awareness in the transition towards sustainability is essential. To overcome the lack of awareness, educational initiatives are needed to inform consumers about the reuse and recycling of E-waste (Islam et al., 2021). The result of this study suggests that some European countries, like Sweden and Denmark, have undertaken campaigns, events, and school education programs to raise awareness. Consequently, social awareness exists regarding properly separating E-waste from other waste streams. This can be inferred as a reason for the high recycling rate in Europe (Kurniawan et al., 2023). Social awareness and increasing demand for green products among people can be inferred as driving forces for firms to embrace CE practices.

7.1.3. Market Demand

The transition toward sustainability is a complex process influenced by multiple dimensions (Geels, 2004, 2012). Similarly, this research indicates that policy and social awareness pressure firms to adopt CE and sustainable practices. Moreover, consistent with previous studies (Rizos & Bryhn, 2022), it is noted that small and medium-sized enterprises (SMEs) display a greater willingness to innovate and adopt CE and sustainability-oriented business models due to their inherent flexibility and adaptability. However, limited financial resources among SMEs may present challenges in effectively implementing CE practices (Rajput & Singh, 2021). Furthermore, the findings reveal that firms have basic knowledge of CE. However, similar to the observations of Geels (2011), the results also indicate that some companies find it challenging to derive clear financial benefits from adopting CE, mainly due to a lack of technical knowledge within their organizations where open opportune for sustainable consulting companies to help firms with the implementation of CE. The adoption of CE among firms is still in its early stage, with ambitious SMEs leading the way (Agency, 2019). However, the adoption is steadily increasing over time. In E-waste management, recycling is well established compared to reuse and remanufacture. Yet, the results suggest that the reuse of E-waste is gaining momentum since it is more beneficial for the firms than recycling because a significant reusable amount of E-waste is possible to extract from the E-waste stream. As the adoption

of CE practices increases, the demand for DTs also rises because DTs offer the potential to share sustainable data with consumers and enhance transparency among stakeholders. This finding is aligns with previous research (Antikainen et al., 2018; Peiró et al., 2021).

7.2. Established Procedure

In the transition towards sustainability, the collaboration between actors is essential because one actor cannot reduce or close the loop of CE; however, multiple actors or ecosystems can (Antikainen et al., 2018). Similarly, the result of this research stresses the importance of collaboration. Particularly, in the context of E-waste management, the EPR policy, mandated by the WEEE directive, resulted in emerging of new actors and better collaboration. The implementation of EPR, however, is different in each country and raised challenges for the adoption of CE (Rizos & Bryhn, 2022). In Denmark and Sweeden, according to the findings, various actors are involved in managing E-waste. These actors include EPR implementers (EPRI), municipalities, compliance schemes, recyclers, collection haulage services, producers, importers of EEE, and consumers (both professional users and private users). Figure 7.1 visually illustrates the interplay among these E-waste management actors and their interactions within the system.

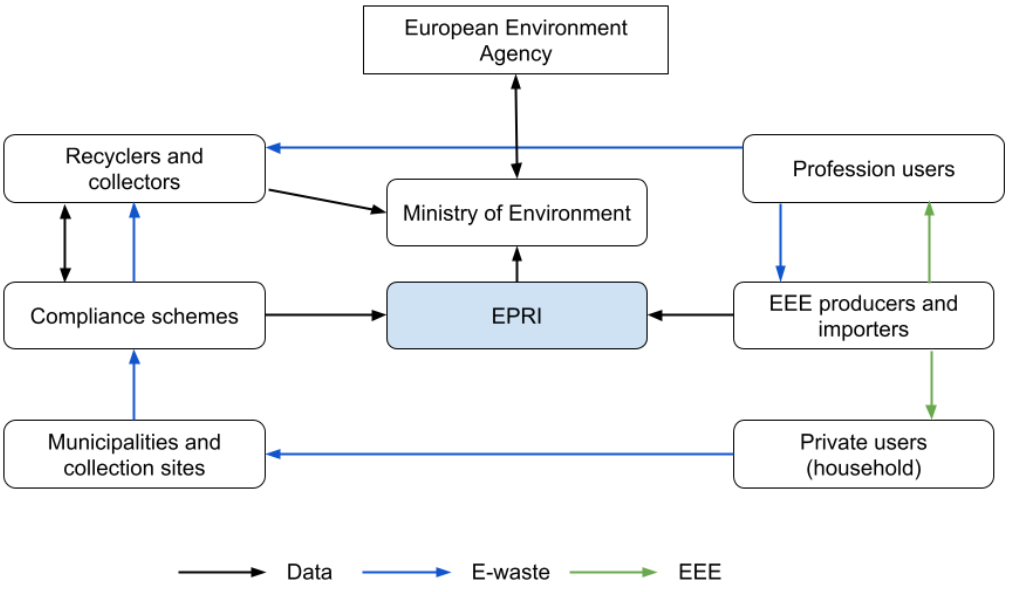

Figure 7.1, E-waste management actors and their interactions

EPRI is responsible for collecting reports about the amount of EEE put in the market and taken back from producers and importers of EEE through an information communication system which has proved to be effective but more initiative and system connection needs to be done. Also, EPRI specifies the amount of E-waste the producers and compliance schemes are obligated to collect from the designated collection sites. Producers are also collecting E-waste from professional users individually or through compliance schemes. Compliance schemes are actors that collaborate with producers to comply with EPR in terms of the collection and recycling of E-waste and also report about the amount of E-waste collected and recycled to the EPRI on behalf of producers. Municipalities are responsible for managing the collections site where privates user expose their E-waste.

7.2.1. Established Procedure Problems

This study indicates that in E-waste management, among other principles of CE, the primary focus of the firms are on recycling solely, this point is overlapping with the previous study (Pant et al., 2020). Recycling is the least ideal method of the waste hierarchy concept. Therefore, the results of this study emphasize the need for greater attention to the reuse principle, as a considerable amount of E-waste can be extracted from the E-waste stream, and reusing it is a less costly alternative than recycling while generating more value for the firms. Reuse is also identified as a possible solution for the reduction of E-waste by (Ankit et al., 2021). In addition, the household collection methods of E-waste is not standard; this means that when the consumer disposes of the E-waste in the collection points, it leads to potential damage, particularly to fragile equipment like screen, and it decreases the chance of reuse, even recycling of E-waste. This collection method also raises the concern that high-value devices could be stolen. Hence, consumers are reluctant to return their devices with sensitive data to the collection points due to fear of losing data with devices. They prefer to keep the E-waste in their houses, particularly smaller devices that are convenient to store. Even if the consumer returns it to the collection point, sometimes they crush it, making it difficult to reuse or recycle.

In terms of monitoring of E-waste management by authorities, in line with Rizos & Bryhn (2022), this study suggests that the lack of enforcement of policies resulted in free riders in the market. In turn, there is a prevalence of unofficial channels for the collection and illegal export of E-waste to developing countries, despite existing regulations that prohibit

such exports. The study indicates that approximately 60 percent of E-waste is collected through official channels, while the remaining portion is managed through unofficial channels. The issue of illegal E-waste export has been highlighted in the work of Srivastava and Pathak (2020) as well, due to a lack of policy in developing countries. However, in this research the high cost of recycling and remanufacturing of E-waste in Europe and the lack of enforcement of policies founded as reasons for exporting E-waste illegally. The study participants recommended issuing a policy to obligate compliance schemes for monitoring and validating reports of producers due to close working relations.

7.2.2. Resistance to Change

Transparency, data sharing, and collaboration among actors is essential for adopting and implementing CE principles (Antikainen et al., 2018). However, the findings of this study in line with this (Vermunt et al., 2019) indicate that incumbents, particularly producers of EEE, exhibit resistance to sharing data with EPRI despite having digitalized processes. This resistance to change or the adoption of innovative solutions could be attributed to incumbents' reliance on existing practices, norms, and technologies (F. W. Geels, 2002; Smith et al., 2010). Regarding data sharing, privacy concerns and competition between actors have also been identified as potential barriers (Antikainen et al., 2018). This study in addition of the mentioned points, expands that producers may resist sharing data due to a desire to retain control and a tendency towards unofficial channels for E-waste collection, which can be more beneficial for producers. For facilitating data sharing, participants of this research recommended issuing regulations mandating data sharing among actors to enhance collaboration and improve E-waste management.

Additionally, the study indicates that producers might be reluctant to adopt barcodes or RFID for product tracking within the lifecycle of products due to perceived high costs. However, it is worth noting that the price of RFID and barcodes has become more affordable with technological advancements. Also, the lack of digitalization of existing incumbents, especially the recyclers, due to the norm and traditional way of doing business is another problem that is the reason for increased the issue of transparency and operation inefficiency.

7.3. Innovative Solutions and Digital Technologies

7.3.1. Potential of DTs in CE practices

The findings of this study are in line with previous research (Uçar et al., 2020; digital waste management, 2020), suggesting that DTs play a significant role in facilitating the transition towards CE. However, it is essential to note that the contributions of other factors such as policy and social awareness should not be overlooked. Building upon existing knowledge (Uçar et al., 2020), this study further highlights the potential of blockchain technology in providing a digital passport for each product, securely and immutably storing information about its origin, composition, and LCA throughout its entire lifecycle. Such information can be utilized by various actors within the CE context. For instance, manufacturers can leverage this information to enable modular design strategies where the components be replaceable and recyclable easily for slowing the loop (Ottoni et al., 2020a) and establish direct take-back systems from consumers, offering a more efficient alternative to the existing collection methods of E-waste. Moreover, recyclers can utilize this data for better separation of E-waste, as it provides information about product composition which will enhance the recycling process. At the same time, consumers can use it to assess the product's sustainability and understand how to repair and recycle it properly.

As mentioned by previous studies, consumers can collaborate in the reduction of E-waste through repairing, reusing, and recycling of E-waste (Islam et al., 2021). This study expands on this by mentioning that DTs can act as a bridge in facilitating collaboration among consumer and producers. By leveraging digital platforms, consumers can choose to lease or loan products instead of purchasing, while manufacturers can offer repair and maintenance services through these platforms. Furthermore, this study revealed that several digital technologies, such as mobile applications, RFID, and barcodes, are already being used to provide consumers with information on how to repair EEE and recycle it properly when it becomes waste. Consumers can scan the barcode or use the mobile application to access the necessary information, a point also highlighted in a study by Modgil et al. (2021). Moreover, integrating the IoT with mobile applications can inform consumers about the nearest empty recycling bins, encouraging them to recycle and promoting sustainable consumption practices. Additionally, one participant mentioned that DTs have

been used to educate waste pickers and teach theme daily life skills, such as basic financial literacy, especially in developing countries.

7.3.2. Role of DTs in Operational Efficiency

This research, in alignment with the findings of a previous study by Borchard et al. (2022), underscores the potential of digital technologies (DTs) in enhancing operational efficiency and enabling data-driven decisions based on real-time data. Unlike manual business practices, DTs facilitate data collection and analysis from various business functions, such as logistics, warehousing, operations, and finance. This data analysis provides valuable insights into the quantity of waste collected, processed, and disposed of in landfills, offering an opportunity to measure the sustainability performance of firms. Moreover, consistent with Borchard et al. (2022), this study suggests that DTs can improve production and resource efficiency through task automation, thereby reducing business operational costs.

This study found that the utilization of DTs in the context of the E-waste management sector remains limited, particularly the blockchain and digital product passports. However, certain software solutions, such as digital platforms for internal business operations, logistics and transportation, and customer relationship management, are implemented within the sector. An illustrative example is the EPRI communication system in Denmark, which has proven to enhance communication among various actors, including producers, compliance schemes, and recyclers, and has effectively facilitated producers' obligation to manage their End-of-Life EEE responsibly, which resulted in a higher rate of E-waste recycling. Nonetheless, there is still a lack of integration with the systems of other actors and the existence of manual data sharing through E-mail and Excel files primarily due to a lack of digitalization and some actors' resistance to adopting DTs and their preference for relying on existing practices and norms (F. W. Geels, 2011). However, participants from digital solution provider firms mentioned that they had developed an integrated suite of applications for managing waste that unifies data from various business functions, including logistics, operation, and finance, through various software and platforms like SAP (procurement system), CRM, and mobile apps. Therefore, in line with previous research (Antikainen et al., 2018; Peiró et al., 2021), the findings suggest that DTs have the potential to enhance collaboration internally within the organizations by sharing real-time

data and unified reports and externally with actors such as manufacturers, recyclers, and consumers, which will facilitate the transition towards CE.

This study identifies several challenges in the current E-waste collection process; EEE gets damaged when consumers dispose of them at collection sites, and there is a risk of devices getting stolen. Thus, consumers are hesitant to return their E-waste with sensitive data. Additionally, manual monitoring of collection containers, particularly at municipality sites, makes it challenging to determine their fill levels. However, in line with previous research (Kurniawan et al., 2023; Maiurova et al., 2022), digital solution providers interviewed for this study highlighted the potential of DTs in improving E-waste transportation and collection methods which help with better recycling. They mentioned the use of IoT to transmit data on bin levels, waste quality, and quantity. Digital platforms, data analytics, and mobile apps are used for driver scheduling and route optimization for E-waste collection. Moreover, new insights from this study include the development of smart bins by certain actors, enabling users to dispose of small E-waste without concern about data loss. Once the consumer disposes of the E-waste, taking back of device from the bin is not allowed, and the company ensures formatting data from devices in a standard manner. However, it is important to note that a secure collection solution has not been widely implemented yet. Moreover, the algorithm for detecting the fire and automatic compression to ensure maximum capacity usage of the bin is also found in this research. Therefore, this study agrees with previous research (Viswanathan & Telukdarie, 2022) that DTs have the potential to enhance the recycling process of E-waste and close the loop of the CE model.

7.4. Limitations of DTs and Challenges of Their Implementation

The research findings, consistent with the previous study (Kurniawan et al., 2023), indicate that DTs are in the maturity phase. However, it also mentioned that some solutions do not fully align with the specific business requirements of E-waste management actors, posing limitations to their widespread adoption. Another notable limitation identified in this research, in line with Antikainen et al. (2018), related to data security and privacy concerns, particularly when sharing data among stakeholders, which raises the concern of data being sold to third pirates. Expanding on this point, this study also found that producers exhibit reluctance in sharing their data with other stakeholders, especially with regulatory authorities, to avoid being in control. These issues will pose challenges in data

sharing among stakeholders, which result in poor communication, transparency, and collaboration among the actors involved in E-waste management. In line with the previous study (Tavares et al., 2009), the concern of unethical decisions and generating false reports by the algorithms and AI is another limitation that this study found. According to Rajput & Singh., (2021), high cost is associated as a barrier to the implementation of DTs. The findings of this study confirm this point and note that high cost is a challenge for the implementation of DTs, particularly for small-sized firms with limited budgets and resources. Infrastructure and culture of technology adoption among the society is another important factor for successful implementation of DTs; where according to the result of this study, it is high in developed countries, particularly in Denmark and Sweeden.

8. Conclusions

The concluding chapter will summarise the study's main findings in the context of the established research objectives and questions. It will also provide a reflective assessment of the contributions and implications of the study, the limitations of this research, and potential avenues for further research. This study aimed to investigate the impact of socio-technical factors on the adoption of CE in E-waste management in European countries by addressing two research questions. The first research question is how do digital technologies influence the transition towards a CE in the E-waste management system. The second question is how key non-technological factors influence the transition toward a CE in E-waste management systems. Notably, this study contributes to the existing body of literature by utilizing the MLP framework to analyze the role of DTs influencing CE principles, mainly recycling in E-waste management, by conducting an empirical study which was the research gap. Moreover, to the author's knowledge, this is the first study that applied the MLP framework to study DTs' role in enabling CE in the E-waste management sector.

The results of this study indicate that DTs have the potential to enable the principles of CE, generally both to slow and to close the loop of CE. However, DTs alone are not the main factor in enabling CE. In terms of closing the loop, mainly blockchain, RFID tags with digital platforms can track the EEE throughout its lifecycle, allowing manufacturers to evaluate the product at each step for modular design. Manufacturers can also establish the take-back of the product from the consumer for reusing or remanufacturing directly from the consumer, solving the existing problems of E-waste collection. In terms of closing the loop, mentioned DTs can provide material composition information for recyclers, thus enhancing the recycling principle of CE. However, blockchain, RFID, and barcode have yet to be adopted in the E-waste management sector because some actors are resistant to change.

The study also suggests that DTs have the potential to improve collaboration, which is essential for the adoption of CE. Companies use integrated software, mobile applications, and digital platforms to gather data from various business functions, facilitating analysis, data sharing, and unified reports among stakeholders to foster collaboration and transparency. In addition, mobile applications and RFID tags are also being used to raise consumer awareness to recycle E-waste properly. However, data sharing between actors in

E-waste management is not standard and is partly manual due to the lack of digitization of some actors' businesses.

Empirical data indicates that DTs can optimize business operations through automation and data-driven decisions making based on real-time data. As a result, there is a notable improvement in resource allocation, leading to reduced operational costs. Furthermore, as per result, the collection method of E-waste is not standard, leading to potential damage and theft of devices. On the other hand, the study found that DTs, such as mobile applications, digital platforms, and the IoT exhibit potential applicability in E-waste management and collection. These technological solutions can enhance E-waste handling, providing opportunities for more efficient and sustainable practices in managing E-waste.

This study contributes to the existing literature by analyzing external factors such as policy, social awareness, and market demand through the lens of MLP, which indicates that technology is not the only factor that impacts the sustainability transition in E-waste management. The study found that climate change pressures governments to enact policies promoting CE adoption. At the EU level, various policy promotes the adoption of CE, like the European green deal. Nevertheless, there is a need for a policy mandating stakeholders to share data and collaborate. In the context of E-waste management, EPR resulted in better E-waste management by shifting responsibility from municipalities to producers to take care of EEE at their end of life. Also, EPR resulted in the emergence of new actors and businesses for effective E-waste management. However, as per result, EPR policy poses challenges in that implementation varies in each country, and the actor's responsibility involved in E-waste management is ambiguous, leading to a lack of collaboration. The study also suggests that the focus of E-waste management actors is more on the recycling principle; however, the reuse of E-waste is more beneficial and less costly, and it is gaining momentum. The study also suggested that increasing social awareness and demand for green products pressure firms to adopt CE. The adoption of CE is in the early stage, but it is increasing steadily, particularly among SMEs.

The scope of this study is limited to the administration aspect of E-waste for recycling; also, due to time constraints, actors such as producers and recyclers are not included. Further research would be interesting to include those actors. Also, the recycling principle of CE for E-waste is more focused, but reuse is gaining momentum. Thus, the author recommends further research focusing on the reuse aspect of E-waste.

In conclusion, while digital technologies have the potential to enable the CE principle, they are not the primary driver. The transition towards CE also requires an effective policy, increased social awareness, collaboration, and demand from the market. DTs have already reached the maturity phase; several solutions have been developed to enhance CE practices. However, the adoption of digital technologies by E-waste actors is limited due to their reliance on conventional methods. The difficulty in enforcing policies and a lack of monitoring are the challenges identified in adopting CE practices in the E-waste management industry.

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10. Appendix

10.1. Appendix 1 Interview questions

General Interview questions

	Question	Description
General	Can you tell me about yourself, your organization, your years of experience, and your role?	
Niche	What digital technologies are you currently using or developing in the area of electronic waste management?	Niche innovation stage
	How did you identify the need for such technologies?	Niche innovation stage
	How do digital technologies impact the development of circular business models in E-waste management? For clarification, methods of collection of E-waste, recycling, and reuse are mentioned.	Niche innovation stage
	In what ways have digital technologies facilitated or enhanced the recycling process and led to higher recycling rates?	Niche innovation stage
	What were the challenges you faced while developing and implementing these technologies?	Resistance for niche innovation
	What was your customers' and stakeholders' overall perception/idea of these technologies?	Niche development stage
	Can you describe the scope and extent of the adoption of digital technologies in electronic waste management in your organization/industry?	Niche development stage
Regime	What are the potential risks and benefits of adopting digital technologies in the E-waste management sector?	Regime stability
	How digital technologies impacted collaboration and partnerships between different stakeholders in facilitating the transition to a circular economy in electronic waste management? / In what ways have digital technologies enabled effective collaboration and partnerships between various stakeholders involved in E-waste management?	Regime Transformation Stage

	Can you share any examples of digital technologies used in collaborations or partnerships in this area?	
	What is the advantage of digital technologies in waste management? The example mentioned, like in the cost of business, efficiency in better management or communication internally or externally.	Regime transformation
	What is the limitation of digital technologies for waste management / what problems digital technologies have created for E-waste management?	
Landscape Level	How do you see the role of digital technologies evolving in E-waste management in the future?	
	What are the potential impacts of digital technologies on the broader E-waste management system? **Followup:** For example, how do DTs impact in logistics, collection, and administration of E-waste?	
	What policies or regulations exist to support/hinder the transition to a circular economy in E-waste management?	Governance level
	In your opinion, what policy changes are needed to foster the adoption of digital technologies for a circular economy in E-waste management?	Governance level
	How can collaboration and partnerships across stakeholders (e.g., governments, NGOs, private sector) support the adoption of digital technologies in E-waste management?	
	How do market conditions influence the adoption of digital technologies in electronic waste management?	
	What are the social norms and cultural values that shape the adoption of digital technologies in electronic waste management? **Followup Questions:** How do digital technologies impact on awareness of consumers?	

Interview questions from Expert for testing and gathering data

Interview for experts were designed to test gathered data from other frims interviewees, or some of the general questions were asked from the experts as well.

	Question	Description
General	Can you tell me about yourself, your organization, your years of experience, and your role?	
Niche	According to interviews that I did with companies (IoT, mobile applications, web applications, systems, AI, big data), are the DTs have been used. In your opinion, what DTs the E-waste management using and how?	
	In your opinion, what is the need for using digital technologies in(E-waste) management companies to enable CE?	Niche innovation stage
	According to other companies' interviews (unified data for better decision making, tracking of product life cycle, enhanced reporting, reduction in business cost) are the potential of DTs for CE, what do you think, how do DTs impact the development of CE in E-waste management?	Niche innovation stage
	In what ways have digital technologies facilitated or enhanced the recycling process and led to higher recycling rates?	Niche innovation stage
	In your opinion, what challenges are the companies facing in adopting digital technologies in CE business model?	Niche innovation stage
	What do you think, are the actors involved in E-waste management are ready for adoption of digital technologies?	Resistance for niche innovation
	What do you think about the potential of digital technologies for E-waste mangement, in administration, finance and logistics?	Niche development stage
	What are the potential risks and benefits of adopting digital technologies in the E-waste management sector?	Niche development stage

Regime

	Communication between stakeholders is important for enabling CE. lack of awareness, fragmented communication channels, and lack of information sharing are the problems that DTs can improve according to the interviews that I did, what do you think about how DTs impact collaboration internally and externally with stakeholders to enable CE?	Regime Transformation Stage
	Can you share any examples of digital technologies used in collaborations or partnerships in this area?	
	What is the advantage of digital technologies in waste management? The example mentioned, like in the cost of business, efficiency in better management or communication internally or externally.	Regime transformation
	What is the limitation of digital technologies for waste management / what problems digital technologies have created for E-waste management?	Regime stability/resistance
Landscape Level	How do you see the role of digital technologies evolving in E-waste management in the future?	
	What are the potential impacts of digital technologies on the broader E-waste management system? **Followup:** For example, how do DTs impact in logistics, collection, and administration of E-waste?	
	European Green Deal, and extended producer responsibility are the regulation for support of CE, in you are opinion, what policies or regulations exist to support/hinder the transition to a circular economy in E-waste management?	Ask this as last question
	In your opinion, what policy changes are needed to foster the adoption of digital technologies for a circular economy in E-waste management?	Governance level
	How can collaboration and partnerships across stakeholders (e.g., governments, NGOs, private sector) support the adoption of digital technologies in E-waste management?	Governance level
	How do market conditions influence the adoption of digital technologies in electronic waste management?	

	What is the status of social awareness in Europe about sustainability/CE, and how the social awareness impact transition toward CE? How do digital technologies impact public awareness about waste and proper waste disposal?	

10.2. Appendix 2 Data Sources

Data Source Identifier in Findings	Company	Resource Title	Date Created	Type of Document
DS_1	ISB Global	ISB Global knowledge hub	N/A	Retrieved 05, 10, 2023, from https://www.isb-global.com/knowledge-hub/
DS_2	DPA -Danish Producer Responsibility	Dual use – registration of electrical and electronic equipment as private or professional equipment	N/A	Retrieved 06,12,2023 from https://producentansvar.dk/en/
DS_3	DPA -Danish Producer Responsibility	Individual compliers' collection of WEEE	06, 2022	Retrieved 06,12,2023 from https://producentansvar.dk/en/
DS_4	DPA -Danish Producer Responsibility	Allocation scheme	N/A	Retrieved 06,12,2023 from https://producentansvar.dk/en/

10.3. Appendix 3 Code book

Themes / Sub-themes	**Description**
1. Climate change	This theme explains environmental concerns and geopolitical instability.
2. Social Awareness	This theme explains social awareness regarding sustainability and environmental change.

2a. Social behavior	"Social behavior" is the sub-theme that explains the actions and attitudes that impact the adoption of CE.
2b. Clients behavior	This subtheme explains the actions, attitudes, and interactions of firms/entrepreneurs that impact in adoption of CE.
2c. Educational programs	This subtheme explains the initiative or activities designed to promote awareness or knowledge of public about sustainability
3. Policy	The "policy" theme describes the laws, regulations, or actions plan enacted by the institutions to achieve sustainability.
4. Market demand	This theme explains the firm's demand and readiness for the adoption of CE and DTs.
5. Established procedure	The main theme "established procedure" demonstrates the current business process and activities of firms involved in E-waste management.
5a. Actors and its responsibilities	This sub-theme focuses on the indication of the actors involved in E-waste management in their responsibility.
5b. Collaboration	The subtheme of "collaboration" underscores the importance of collaborative efforts among diverse actors involved in E-waste management in the adoption and implementation of CE.
5c. E-waste collection	The "E-waste Collection" subtheme explains the established method of E-waste collection.
6. Established procedure problems	The theme "Established process problems" explains the challenges associated with the existing business processes of incumbents in E-waste management.
6a. Quality control	The "quality control" subtheme describes the method of monitoring and controlling E-waste management and its impact.
6b. Policy limitation	The subtheme "policy limitation" explains the challenges the policy created for the actors involved in E-waste management.
6c. Need for policy	The subtheme of "policy necessity" explains the general barriers and constraints encountered in the established business procedures concerning E-waste management, underscoring the imperative for novel policy interventions.
7. Role of DTs in operational efficiency	This theme elucidates the role of DTs in optimizing the efficiency of E-waste management procedures.

7a. Role of DTs in logistics	This subtheme explains the potential of DTs in the optimization of logistics and transport in E-waste management.
7b. Role of DTs in collaboration and information sharing	This subtheme describes the impact of DTs in information sharing and collaboration among actors and consumers.
8. Resistance to change	The theme "resistance to change" elucidates the actors resistant to the adoption of CE and DTs
9. Strategies for reduction of E-Waste	This theme explains various strategies that can be applied for better E-waste management.
10. Potential of DTs in enabling CE practices	This theme explains the potential of DTs in enabling CE principles such as reduce, reuse, and recycle.
11. Role of DTs in raising consumer awareness	This theme describes the potential of DTs in raising consumer awareness regarding sustainability issues and how DTs can be used to help consumers better reuse and recycle E-waste.
12. Barriers to DTs	The theme "barriers to DTs" explains the shortages of DTs and the challenges the actors encountered while adopting them.
12a. Limitation of DTs	This subtheme describes the limitation of DTs, e.g., security and privacy issues.
12b. DTs implementation challenges	This subtheme explains the challenges that firms encountered while adopting DTs