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Exploring the role of DPPs in enhancing e-waste management within the consumer electronics sector: a pathway to circularity

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Masters in Studies of the Environment and Sustainability

Supervisor:
PhD Cristina Maria Paixão de Sousa, Associate Professor, Department of Political Economy, Iscte – University Institute of Lisbon

October, 2024

CIÊNCIAS SOCIAIS
E HUMANAS

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ABSTRACT

There is a growing e-waste crisis, with millions of tons of electronic waste discarded yearly. The amount of e-waste reached 62 billion kg worldwide in 2022, with only 13.8 kg being formally collected and recycled. Europe is the biggest generator of e-waste per capita, reaching 17,6 kg in 2022, with only 42,8% of this waste being formally collected and recycled (Baldé et al., 2024). One of the most significant contributors to this challenge is consumer electronics, reaching 10,5 billion kg worldwide. With technological advancement, device consumption is only rising; product lifecycles become shorter and old appliances become rapidly obsolete. As a way to try altering that, and as an alternative to the linear economy, circular economy (CE) emerges.

Because of the current gaps in e-waste management, digital product passports (DPPs) are introduced in the EU as part of the Ecodesign for Sustainable Product Regulation (ESPR), which entered into force in July 2024. Therefore, this research explores the role of digital product passports (DPPs) in improving e-waste management and promoting circular economy practices in the consumer electronics sector. It aims to explore the effectiveness of DPPs in managing e-waste, determining the benefits, limitations and challenges and evaluating how DPPs can help promote a circular economy.

In order to do that, three reports and two interviews with crucial stakeholders were analysed. A thematic analysis of the qualitative data was realised, and seven themes emerged. The research showed that DPPs indeed contribute to e-waste management in the consumer electronics sector by ensuring transparency through the entire value chain, enhancing traceability throughout the product lifecycle and supporting better components and material tracking. Moreover, they proved to be beneficial in reuse and repair by providing the appropriate data. Additionally, DPPs are shown to be closely aligned with CE principles, supporting transparency in product lifecycle data and motivating manufacturers to develop more circular products.

However, the results also show that there are some challenges to keep in mind: DPP implementation costs could be high, especially for SMEs, and there is a dilemma between data transparency and data confidentiality and the trouble of integrating the DPPs across different industries and systems.

Keywords: e-waste, circular economy, digital product passports, consumer electronics

RESUMO

Há uma crescente crise de resíduo eletrônico, com milhões de toneladas descartadas anualmente atingindo 62 bilhões de kg em todo o mundo em 2022, com apenas 13,8 kg sendo coletados e reciclados formalmente. A Europa é o maior gerador de lixo eletrônico per capita, atingindo 17,6 kg em 2022, com apenas 42,8% desses resíduos sendo coletados e reciclados formalmente (Baldé et al., 2024). Um dos contribuintes mais significativos para esse desafio são os eletrônicos de consumo, atingindo 10,5 bilhões de kg em todo o mundo. Com o avanço tecnológico, o consumo de dispositivos só está aumentando; os ciclos de vida dos produtos se tornam mais curtos e os aparelhos se tornam rapidamente obsoletos. Como forma de tentar alterar isso, e como alternativa à economia linear, surge a economia circular (EC).

Devido às lacunas atuais na gestão de resíduos eletrônicos, os passaportes digitais de produtos (DPPs) são introduzidos na UE como parte do Regulamento de Ecodesign para Produtos Sustentáveis (ESPR), que entrou em vigor em julho de 2024. Portanto, esta tese explora o papel dos DPPs na melhoria da gestão de resíduos eletrônicos e na promoção de práticas de economia circular no setor de eletrônicos de consumo. O objetivo é explorar a eficácia dos DPPs na gestão de resíduos eletrônicos, determinando os benefícios, limitações e desafios e avaliando como os DPPs podem ajudar a promover uma economia circular.

Para isso, foram analisados três relatórios e duas entrevistas com partes interessadas cruciais. Foi realizada uma análise temática dos dados qualitativos, e surgiram sete temas. A pesquisa mostrou que os DPPs de fato contribuem para a gestão de resíduos eletrônicos no setor de eletrônicos de consumo, garantindo transparência em toda a cadeia de valor, aprimorando a rastreabilidade ao longo do ciclo de vida do produto e apoiando melhores componentes e rastreamento de materiais. Além disso, eles provaram ser benéficos na reutilização e reparo, fornecendo os dados apropriados. Os DPPs também demonstram estar estreitamente alinhados com os princípios da CE, apoiando a transparência nos dados do ciclo de vida do produto e motivando os fabricantes a desenvolver produtos mais circulares.

No entanto, os resultados também mostram que há alguns desafios a serem considerados: os custos de implementação do DPP podem ser altos, especialmente para PMEs, e há um dilema entre a transparência e a confidencialidade dos dados e o problema de integrar os DPPs em diferentes setores e sistemas.

Palavras-chave: resíduo eletrônico, economia circular, passaportes digitais de produtos, eletrônicos de consumo

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GLOSSARY

CE - Circular Economy

CEAP – Circular Economy Action Plan

EEE - Electrical and Electronic Equipment

EoL – End-of-Life

EU - European Union

EPR - Extended Producer Responsibility

ESPR – Ecodesign for Sustainable Product Regulation

LCA - Life Cycle Assessment

SME - Small and medium-sized enterprise

VC – Value chain

WEEE - Waste from Electrical and Electronic Equipment

INTRODUCTION

People's lives constantly change with digital transformation, and new technologies are developed daily. Several people own multiple electronic appliances, from fridges and televisions to smartphones, smartwatches and video games. Because of this growing amount of electronics being put on the market, the amount of Waste from Electrical and Electronic Equipment (WEEE), also known as e-waste, consequently grows. E-waste is one of the fastest-growing waste streams worldwide, with 3-5% annual growth rates. In 2022, the amount of e-waste reached 62 billion kg worldwide, with only 13.8 kg being formally collected and recycled (Baldé et al., 2024). This fast increase is driven by technological developments, economic growth, and increased accessibility to electronics (ibid.)

Europe generates the most significant amount of e-waste per capita, reaching 17,6 kg in 2022. However, only 42,8% of this waste is formally collected and recycled (Baldé et al., 2024). Although Europe has the most considerable collection and recycling rate among all other continents, it still made relatively little progress towards reaching its target. Because more than half of the e-waste produced is not formally collected and recycled, most e-waste is handled informally. This results in mercury and plastics comprising flame retardants being released into the environment, impacting both the environment and our health (Rautela et al., 2021.

Consumer electronics is a big part of the e-waste problem. It refers to all devices used for information, communication or entertainment purposes (Statista, 2023). Although not the most considerable e-waste stream in kg, it has a significant contribution to the problem. Overall, they count for 10,5 billion kg worldwide, with only 2,5 billion kg being formally dealt with (Baldé et al., 2024). Technology is constantly developing, and the consumption of electronic devices is continuously increasing while older appliances become obsolete. They usually have shorter lifecycles because of purely planned obsolescence or faster innovation (Meloni et al., 2019). Even if consumer electronic devices still work, they are replaced quickly because of new features or marketing (ibid.).

Circular economy (CE) is an alternative to the current linear economic model. It focuses on a 'reduce, reuse and recycle' instead of a 'take, make and dispose' model. (Ghisellini et al., 2015). Thus, CE practices focus on keeping products and materials in use for as long as possible, reducing the need for raw materials and lowering the amount of environmental

impact. The EU, as of 2020, released a Circular Economy Action Plan (CEAP) with a package of measures in order to contribute to assisting the EU in reaching all its environmental goals, doubling the material use circularity rate and reaching the target for energy efficiency by 2030 (European Commission, 2020). One of these measures is the Ecodesign for Sustainable Products Regulation (ESPR), in which the digital product passports (DPPs) were first introduced. The DPPs are a digital tool that can store product information about its components, lifecycle and environmental impact. This allows products to be monitored across the entire value chain (VC).

As stated before, there are currently gaps in e-waste management. The majority of e-waste in the EU is not being formally collected and recycled, leaving many valuable materials to go to waste. Furthermore, when it comes to recycling processes, dealing with e-waste is often inefficient since most consumer electronics are not easily disassembled, making it harder to recover valuable materials and repair these appliances (Baldé et al., 2024). Overall, there is a lack of transparency about product information regarding electronics (ibid.).

Therefore, integrating circular economy practices, mainly through the implementation of DPPs, significantly increases the effectiveness of e-waste management in the consumer electronics sector (Psarommatis & May, 2024). This integration not only contributes to the sustainability of businesses by reducing waste and optimising resource use but also opens new opportunities for the transition to circular models. The adoption of DPPs can lead to higher e-waste recycling rates, improved product lifecycle management, and increased consumer awareness of sustainability issues (ibid.). Furthermore, this shift towards circular economy practices is expected to align closely with EU regulations, promoting compliance and fostering innovation in sustainable product design and e-waste management strategies.

This study contributes to a larger circularity and sustainability agenda delineated in the EU CEAP and the ESPR by investigating the role of DPPs in reducing e-waste and optimising product lifecycle management. This topic is significant for academia and several stakeholders in the electronics sector, such as policymakers and businesses. Since this is a new topic and seeing that the DPPs for electronics will only likely be implemented in 2026, there are not many research or consistent information about it.

In this context, this research aims to answer the question: How do Digital Product Passports (DPPs) contribute to improving e-waste management and promoting circular economy practice within the consumer electronics sector? As stated before, consumer electronics are a relevant case to illustrate the practical implications of the DPP due to their high environmental impact, short product lifespans, and large waste footprints. Thus, this

research aims to explore the effectiveness of DPPs in managing e-waste, determine the benefits, limitations and challenges and evaluate how DPPs can help promote a circular economy.

The remainder of the dissertation is organised into five chapters. Chapter one will focus on the theoretical framework that is relevant to the topic, going deeper into e-waste management, circular economy and DPPs. Chapter two will focus on the methods used to gather and analyse the data, focusing on why specific approaches were chosen and how they were carried out. The third chapter will highlight the most important results from the data analysed, both from the interviews and the reports. These are presented in themes that emerged from the data analysis. Chapter four will present a discussion connecting the findings presented in the chapter prior and existing research and theories. Finally, the conclusion summarizes the main findings and points the limitations of the research, and recommendations for future research.

CHAPTER 1

LITERATURE REVIEW

1.1 Circular Economy in the Consumer Electronics Industry

1.1.1. Introduction to Circular Economy

1.1.1.1. Historical development and evolution of CE

The concept of circular economy originates from various schools of thought. Boulding (1966) and Pearce and Turner (1989) were the ones who introduced the concept of CE system to address the linear economic model of 'take, make, dispose'. From its roots in ecological and environmental economics and industrial ecology, the concept of CE has evolved significantly.

The latter's idea about CE was that it was crucial for maintaining sustainability and human life on this planet. Beyond that, CE can also be observed in Industrial Ecology (IE) and General Systems Theory, which focus on the importance of closed-loop systems as well as the combination of sustainable development and economic activities (Ghisellini et al., 2015). However, it is important to note that research on the implementation of CE has been and still is largely rooted in the IE idea of benefits analysis with regard to physical flows as opposed to monetary. Since then, many other concepts have emerged through three main actions, i.e. the 3R principles: reduction, reuse and recycle (Ghisellini et al., 2015).

Whereas CE originated as a theoretical framework focused on resource efficiency and minimizing waste, it has since grown into a more comprehensive model that aims to balance economic growth with environmental sustainability. This evolution has been marked by varying approaches to CE implementation across different regions, with on the one hand China adopting a top-down approach driven by national policy, while Europe and Japan have taken more bottom-up approaches through environmental policies and industrial practices (ibid.). Overall, the CE concept is in continuous development, integrating new ideas from regenerative design, performance economy, and other emerging frameworks, reflecting an ongoing transition toward more sustainable economic systems (ibid.).

1.1.1.2 Definition

At the same time as the concept has gained traction among scholars and practitioners over the years, its definitions have multiplied. Currently, there is significant conceptual ambiguity, with different stakeholders interpreting the concept in diverse ways and no unique definition (Neves & Marques, 2022). There are more than 114 definitions of CE across 17 dimensions encompassing commonalities and differences (Kirchherr et al., 2017). CE is most commonly associated with the activities of reducing, reusing, and recycling, but often lacks a systemic perspective and clear links to sustainable development. It is important to maintain coherence in its conceptualization since, without it, there is a risk of it becoming diluted or even collapsing under its conceptual contradictions (ibid.).

The concept of Circular Economy (CE) used in this dissertation can be conceptualised as an economic system that aims to eliminate waste and promote the continuous use of resources. It brings an alternative to the current economic model of 'take, make and dispose', which is the 'reduce, reuse and recycle' model. (Ghisellini et al., 2015). It relates to reducing the access to primary energy, waste and materials by promoting the improvement of eco-efficiency and consumption; reusing products that are already on the market, without creating more waste; and recycling all waste in new products or materials. This new model focuses on a more sustainable development, in which technology, economics, environment and society work together (Kirchherr et al., 2017).

To complement this conceptualization, according to the Ellen MacArthur Foundation (2013), CE encompass a system in which materials never become waste and nature is constantly regenerated. There is a need to keep materials and products in circulation for as long as possible. This can be done through processes such as repair, maintenance, recycling, composting etc. The circular economy tackles not only climate change but also pollution, waste and biodiversity loss. It, directly and indirectly, decouples the consumption of limited resources from economic activity (ibid.). As stated before, our economy is currently linear, we take materials from the Earth, we make products and, ultimately, throw them away as waste. In a CE, the goal is to, primarily, have no waste. There need to be a substantial change in the way we manage resources, design of products, and how to deal with the waste. By doing this, circular economy will thrive, benefitting humans and nature and not crossing the limits of the planet (ibid.).

Therefore, although there are various conceptualisations of CE, for the sake of this dissertation the focus will be on CE defined as an economic model aimed at eliminating waste,

maximising the use of resources at their highest value for as long as possible, and rejuvenating natural systems (Circle Economy, 2024).

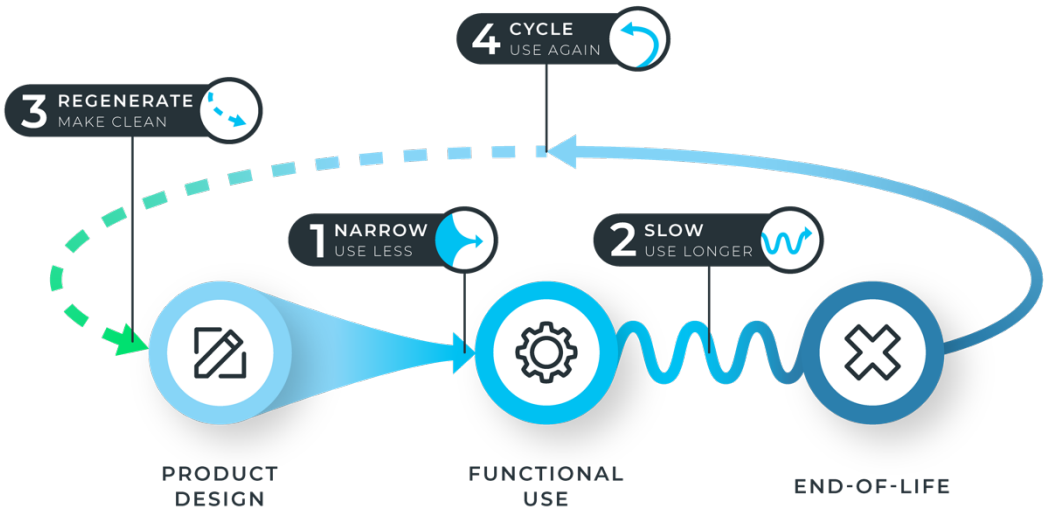
1.1.1.3 Circular Economy principles

As stated before, although there are a growing number of circular initiates across the world, the concept of circular economy remains uncertain. In order to have a better understanding of the concept, it is important to understand what principles guide its understanding. It is important to look at CE as an economic model focused on eliminating waste, maximising resource use at their highest value for as long as possible, and rejuvenating natural systems (Circle Economy, 2024). This approach mirrors nature, where waste does not exist and all materials hold value, contributing to life in various ways. By effectively implementing these strategies, we can significantly reduce the number of materials needed to meet societal demands. It comes as an alternative framework for living within the means of the planet while still supplying for the world population (ibid.).

In this context, the CE is based on four main principles, as shown in Figure 1 (ibid.): i) *narrow flows*, meaning use less resources; ii) *slow flows*, meaning use resources for longer; iii) *regenerate flows*, meaning use cleaner resources; and iv) *cycle flows*, meaning use resources again.

Narrow flows refer to using less resources through efficient design, for example, designing lightweight products; adopting circular business models, such as adopting sharing and rental services; and/or increased reuse of materials to avoid over consumption. By applying these strategies, it is easier to reduce both material use and greenhouse gas emissions (ibid.). *Slow flows* relate to extending the lifespan of products through durable design, maintenance and repair. It involves making the most of already existing products, such as buildings, clothing and electronics, through strategies like remodelling and refurbishing. This allows for the optimization of resource use and the reduction of extraction rates. *Regenerate flows* refer to using cleaner, regenerative resources instead of fossil fuels and toxic materials. This includes activities such as transitioning to clean energy and practising regenerative agriculture, but also opting for regenerative materials such as wood over environmentally harmful ones like plastic. As a result, this can help sustain natural ecosystems (ibid.). Finally, *cycle flows* relates to reusing materials and products at the end of their life, creating a circular flow of resources. This involves better collection and reprocessing of materials and maximising their value through upcycling. Designing products for recyclability and disassembly facilitates both reuse and recycling, ensuring efficient resource use throughout their lifecycle.

Figure 1 - Four Key Circular Flows



Source: Circle Economy (2023) [https://www.circle-economy.com/blog/beyond-the-energy-transition].

To go deeper into the concept of CE and to display the entirety of strategies possible to transition to a more circular world, the Key Elements Framework (KE) was created, building on the key flows explained above (Circle Economy, 2021). This is a conceptual framework consisting of eight elements of circularity that can be applied at several different levels of intervention, such as national, regional, business, product etc. These elements are divided into three core and five enabling elements. Core elements are the activities that directly handle physical flows, including prioritising regenerative resources, stretching the lifetime, and using waste as a resource. Enabling elements are those that remove certain obstacles or create conditions for the core actors, including design for the future; rethink the business model; incorporate digital technology; team up to create joint value and; strengthen and advance knowledge.

Table 1 - 8 Key Element Framework

Core elements	
Stretch the Lifetime	Optimize resource use by extending product life, reducing extraction rates
Use Waste as a Resource	Use different waste streams as secondary resources

Enabling elements	
Design for the Future	Systemic design perspective, durable materials, minimize waste during production
Rethink the Business Model	Deliver services/products using business models and maximizing value
Incorporate Digital Technology	Enable resource tracking, supply chain connections, and circular models with technology
Team Up to Create Joint Value	Collaborate within and across industries to enhance transparency and shared value.

Source: Adapted from Circle Economy (2021). [https://www.circle-economy.com/resources/the-key-elements-of-the-circular-economy-framework].

In the interest of this dissertation, only the elements that directly relate to e-waste management will be studied. From the core elements, it is crucial to focus on *using waste as a resource*, meaning to use different waste streams as secondary resources and retrieve waste for repair and reuse. It is also important to focus on *stretch the lifetime,* meaning optimizing resource use by extending product life, reduce extraction rates. These two core key elements are essential in the transition towards a circular economy. They focus on the importance of designing products to last longer, by using more durable materials for creating designs that are easy to repair, always ensuring that products' parts can be replaced (Circle Economy, 2021).

In relation to the enabling elements, there are four that we should focus on. First of all, *design for the future*, which focuses on the design process, utilizing the right materials and on extending the lifetime of products. It consists of designing out waste meaning reducing waste during production and use, as well as design for cyclability and durability, meaning designing to facilitate multiple product and material lifecycles and use and making sure products are made to last and tolerate longer use periods. Besides design, it is also important to *rethink the current business model*. There is a need to contemplate on new ways to create more value in both products and services (ibid.). Therefore, delivering services or products using business models that maximize their value. The third enabling element relates to *incorporating digital technology* to enable tracking and optimization of resource use, reinforce supply chain

stakeholders' connections and the implementation of circular models (ibid.). It can be online, digital platforms in which technologies are used to build a connection between stakeholders and improve information sharing; or technologies which are used to collect and analyse existing data and present insights about resource use (ibid.). Lastly, it is crucial *to team up to create joint value*. This implies working together throughout the supply chain in order to enhance transparency and create a shared value. This could mean collaborating internally or with other industries, collaborating with consumers, with the government or with the community.

Therefore, the Key Elements Framework is unique in including enabling elements that address persistent obstacles to implementing core circular economy principles. These obstacles include reliance on traditional, linear economic incentives, inadequate systems for tracking and recovering resources, and a general lack of awareness and knowledge about the circular economy (Circle Economy, 2021). Enabling elements help to overcome these challenges, thereby accelerating the adoption of circular practices.

1.1.2 Circular Economy in the consumer electronics industry

1.1.2.1 Overview of the consumer electronics industry

The consumer electronics industry is worth US$950 billion worldwide and is expected to reach US$1.13 trillion in 2025 (Statista, 2023). This a trillion-dollar industry that is constantly growing, with companies like Apple, Samsung and Sony leading the way (ibid.). Although it seems, sometimes, saturated with innovative products and companies, it does not stop society from investing in electronic products (ibid.).

Consumer electronics refers to devices used for information, communication or entertainment purposes (Statista, 2023). It goes from a broad range of products comprising electronic circuit boards designed for non-commercial to personal use such as AR glasses, VR headsets, smartwatches, phones, headphones, computers, TVs etc. It concerns every device used for communication, information and entertainment (ibid.). Within this market, there are several submarkets, attracting a different number of customers and generating a different revenue. At first, there is the *telephony* market, comprising all smartphones and generating the most revenue of the industry, namely almost 500 billion US dollars worldwide in 2023 (ibid.). Smartphones are followed by *computing,* US$218 billion and *TV, radio and multimedia*, US$190 billion.

Now, that technology is developing a lot faster and with better quality, there are different consumer electronics industry sub-categories that are gaining attention. One example is the development of equipment that are more immersive and provide new realities, namely from the category of extended reality (XR) (ibid.). These could be augmented reality (AR), virtual reality (VR) and mixed reality (MR). This set of technologies can either expand our current realities by creating a completely new immersive experience or by merging our reality with the virtual world. The revenue comprising all XR sub-categories reached, in 2018, US$ 4 billion. In 2023, it tripled its market revenue going up to US$12 billion. Overall, there is a growing number of consumer electronics entering the market each year, however, the way these products are being produced, consumed and disposed is not at all sustainable (Forti et al., 2020).

1.1.2.2 Current linear economic practices and their limitations

It is clear that the current linear economic model of production, consumption and disposal is no longer suitable. It is based on a *take, make, dispose* approach that focuses on extracting raw material, using them to manufacture products and, once these products are no longer functional or wanted, disposing of these products. There are five main linear practices in the consumer electronics industry.

Firstly, the consumer electronics industry depends heavily on mining and finite resources extraction such as lithium, cobalt and other metals essential for circuits, batteries and processors. However, these activities have certain limitations such as their high carbon footprint since mining contribute significantly to greenhouse gas emissions (Ellen MacArthur Foundation, 2018). Furthermore, related to the resource consumption, since many of the materials are non-renewable and extracting them harms the environment.

Secondly, consumer electronics are mostly produced on a larger scale and designed for fast obsolescence as a result of continuous technological advancement or simply because products are out of trend (Meloni et al., 2019). Consequently, this can lead to a growing amount of e-waste. If electronics have shorter life cycles, more will be discarded. It is estimated that, per year, 50 million tonnes of electronic waste is generated (Baldé et al, 2024). Another limitation is the low recyclability rate (Meloni et al., 2019). Many products are difficult to disassemble and also contain hazardous materials such as mercury and lead, which limits their efficient recyclability. Besides that, these toxic substances are extremely harmful to our health and the environment (Baldé et al, 2024).

Thirdly, many consumer electronics are designed with few repair and upgrade options (Meloni et al., 2019). This makes it more difficult to repair devices when they break or to add

new features over time. The first problem is that customers are more likely to discard their devices or buy new ones when these are too expensive or difficult to repair. Another problem is that components which might still function, such as batteries and screens, are discarded in its entirety with the equipment resulting in inefficient resource use.

Lastly, once a product reaches its end-of-life, it is usually discarded into either incinerators or landfills instead of being handled and recycled or repurposed (Ellen MacArthur Foundation, 2018). Because e-waste contains toxic substances, it can leach into water and soil, polluting ecosystems and contaminating human health (ibid.). Beyond that, there are several valuable materials that are often lost in landfills instead of being recovered for reuse, leading to more raw material extraction (Baldé et al, 2024). Additionally, it is only a small quantity of e-waste that is properly and efficiently recycled due to different reasons such as lack of infrastructure or regulation (ibid.).

1.1.2.3 Application of CE principles in consumer electronics

In quite short time, electronic products have become a 'must have' in our daily lives. They are constantly changing the way we live, work and have fun (Ellen MacArthur Foundation, 2018). Although their utility is very beneficial for us, most of these products are handled as disposable (ibid.). There is a need to create a different electronics system, one that works within our planetary boundaries (ibid.). The challenge is that these products are becoming more complex every day, and although they are made from metals and plastics, they are being used for shorter periods of time. Beyond that, the existing disposal practices indicate that most of the resources, energy and value incorporated in these products is lost (ibid.). Consequently, the amount of e-waste generated in the process grows exponentially (Ellen MacArthur Foundation, 2018).

Overall, there are several opportunities to change from this linear economic model to one derived from circular economy principles. The latter requires a gradual decouple of economic activity from consuming finite resources and designing out waste. Therefore, to apply the CE principles in the way we design, produce and utilize electronics, there is a need for more innovation in different areas such as design, business models and reverse logistics (Circle Economy, 2024).

When it comes to keeping products in use for longer, there is a need to rethink the design of products. The first strategy companies adopting to achieve this is to offer repair and refurbishment, either by users, such as Fairphone with its modular smartphones where everything needed is available online (Fairphone, 2023), or by technicians, as Apple does

(Makov, & Fitzpatrick, 2021). Whether the repair and refurbishment are made by users or technicians, both ways have the capacity to support a more circular use of resources, since the longevity of the product could be extended (ibid.). It is important to keep in mind that a certain degree of repairability is needed in both strategies.

Rethinking the design is also crucial for material recovery in the recycling process when the product reaches its EoL (Ellen MacArthur Foundation, 2018). There are several recycling technologies being developed which guarantee increased profit and decrease the environmental impact of current recycling approaches (ibid.). To be able to recover the greatest number of materials possible, product design is crucial. The design must enable both identification and separation of the materials which could be a challenge if all the materials re fused together (ibid.). By increasing the quality of materials together with smart design for recycling, there is a better economic case for recovering electronics after their EoL.

If products continue to be landfilled by users after the first use or are being forgotten in their closet, the impact of design is somewhat restricted. Thus, adopting new business models and applying reverse logistics is crucial to enhancing product circularity (Baldé et al, 2024). In terms of circular electronics, there is an increasing need for seizing residual value and/or utility. Thus, following that thought, business models are adjusting so that the manufacturer can maintain both ownership and responsibility of the product (Ellen MacArthur Foundation, 2018). This can lead to high product recovery as well as reuse rates (ibid.). Consequently, adjusting business models can lead to higher value captured in electronic products, while establishing a new customer-manufacturer relationship and retaining resources for longer in use.

Lastly, logistics is also a crucial part of product circularity. Product take-back, for example, is already being adopted as part of companies' business models (ibid.). Reverse logistics, in this case, plays a crucial role in the circular economy by returning the product to the manufacturer for repair, recovery, recycling or disposal (ibid.).

1.1.3 Challenges and opportunities in the transition towards circular models in consumer electronics

There are several barriers for the adoption of circular economy practices in the consumer electronics industry stemming either from economic, technological, regulatory or cultural challenges (Kirchherr et al., 2017b). When it comes to economic challenges, there are four main categories (Rizos & Bryhn, 2022). First, implementing circular economy practices usually requires considerable upfront investment in infrastructure, technology and redesign of

supply chain, deterring business from transitioning. Second, many times businesses encounter unclear or limited financial incentives for undertaking CE practices, namely refurbishing, remanufacturing or recycling products. Next to that, there is the fact that for efficient collection, transportation and treatment of e-waste can be extremely expensive and the logistics can be complex (ibid.). Therefore, reuse and recovery models become less financially feasible. Lastly, manufacturers may look at CE models, of durability, reuse and repairability, as a 'missed opportunity' on increasing product sales, especially for industries focused on fast innovation.

There are also technological barriers that should be addressed (ibid.). Many of the electronics produced are designed for aesthetics, cost-effectiveness or performance, not for easy disassembly, recycling and repair (Rizos & Bryhn, 2022). On that account, to support circular business models, new expertise and new technologies should be explored. Other than that, in terms of recycling, there is a lack of technologies (ibid.). Whereas there is recycling for fundamental materials such as metals, there is a lack of technologies to recycle complex mix of materials that are also used in electronics manufacturing (ibid.). Although, recycling technologies are constantly improving, there are still challenges to efficient recovery technologies for certain materials, in addition to their high cost. Finally, there is limited standardization of parts when it comes to consumer electronics (ibid.). This makes refurbishment, repair and parts reuse extremely difficult and less efficient, making it hard to attain economies of scale in circular business models.

Beyond economic and technological challenges, there are also policy and regulatory barriers. When it comes to e-waste management and material reuse, CE initiatives face different regulations and policies across different countries and regions (Rizos & Bryhn, 2022). One example is the WEEE Directive in the EU and because of its implementation flexibility at the national level, has resulted in different regulation and enforcement across different countries (ibid.). This lack of global alignment on policies makes it more difficult for multinationals to implement them. Another example is the Extended Producer Responsibility (EPR) laws, that hold manufacturers accountable for the end-of-life of the products they place on the market, and again is not present and enforced consistently across different regions (ibid.). Furthermore, there is a constant absence of policy actions and compliance or enforcement with already existing legislation, making regulations a barrier to adopting CE (ibid.).

In terms of behavioural and cultural challenges, there are three main challenges that should be stressed. First of all, consumers prefer new products (Kirchherr et al., 2017b). The consumer electronics industry is guided by demand for the newest devices, caused mainly by short lifecycle of products and marketing (ibid.). Beyond that, most of the times, consumers

are reluctant to buy used or refurbished electronic products because of concerns about their quality or performance (ibid.). Another barrier is the consumers' lack of awareness (Rizos & Bryhn, 2022). Some consumers are not aware of both CE principles as well as the environmental impact of their consumption patterns, limiting the demand for more circular and sustainable products. Moreover, there are several CE models that promote leasing products or product-as-a-service models, which, for consumers, might not be ideal since they would like to own their electronics (ibid.).

Overall, the majority of companies remain strongly invested in linear business models and might be opposed to transitioning to circular ones because of fear or hampering the revenue streams (Kirchherr et al., 2017b). In order to shift towards a circular economy, there is a need for all stakeholders to collaborate and work together.

1.2 E-Waste Management in the EU

1.2.1 Understanding e-waste

1.2.1.1 Definition and classification of e-waste

According to the Global E-Waste Monitor (2024), Electrical and Electronic Equipment (EEE) relates to all products that possess electrical components or circuitry and a battery or power supply. It includes several different appliances used in business as well as households. A few examples are washing machines, refrigerators, mobile phones, computers and headphones. We are in a constant process of digital transformation and electronification, with new equipment and new technologies constantly changing the way we are living, working and socialising (ibid.).

EEE includes numerous products each consisting of unique materials, way of disposal and recycling methods. It becomes WEEE or e-waste as soon as it has been discarded as waste by its owner without the intention of reusing it. According to the UNU-KEYs, there are 54 product categories which are grouped in 6 general categories that generally match their waste management features (Baldé et al, 2024). First of all, temperature exchange equipment comprising refrigerators, air conditioners etc.; secondly, lamps; large equipment including washing machines, photovoltaic panels, stoves, etc.; small equipment including toasters, electric toys, microwaves, e-cigarettes etc.; screens and monitors referring to televisions, laptops, tablets; and lastly, small IT and telecommunication equipment including mobile phones, computers, routers and printers (ibid.).

To go further into this categorisation and for the sake of this dissertation, a broad categorisation of *consumer electronics* will be applied. As stated before, these include all devices used for communication, entertainment or information purposes, such as televisions, computers, smartphones, tablets, cameras, wearables, smart speakers (Statista, n.d).

Despite the fact that e-waste is rather well-defined, there is still uncertainty on the distinction between waste and non-waste, mainly for policy and economic decisions (Baldé et al, 2024). On the one hand, not everything that is discarded by the owner is unusable; some devices still work and those that do not can be repaired. On the other hand, not all usable equipment has a market value as it may be obsolete. When it comes to policy, there is a need to distinguish between waste and non-waste because different national laws regulate the transboundary shipment of products. These movements should be encouraged when equipment can be repaired and reused, expanding the lifespan of products and, consequently, reducing environmental impact (Baldé et al., 2024). Nevertheless, falsely stating that products can be repaired and reused when they cannot, or shipping equipment to somewhere where there is no market has led to a growing quantity of e-waste globally, especially in places where there is no infrastructure for proper management (ibid.).

1.2.1.2 Global and regional e-waste statistics

In 2022, global e-waste generation increased five times faster than documented recycling efforts, reaching a record of 62 billion kg (Baldé et al., 2024). From this waste, 13.8 billion kg (22.3%) was properly collected and recycled, with the remainder posing great health and environmental risks. Additionally, in only 12 years the amount of e-waste generated worldwide doubled, reaching 62 billion kg in 2022 (ibid.). By 2030, e-waste is supposed to grow by 32% to 82 billion kg (ibid.). The problem is that the increase in e-waste amount is outpacing the growth in products formally collected and recycled (ibid.). Although the amount of e-waste properly collected and recycled has increased, from 8 billion kg in 2010 to 14 billion kg in 2022, it is still a very low number when comparing with the number of electronic products placed on the market (ibid.). There is a critical gap in e-waste management infrastructure, and, without urgent global action, there will be even more significant environmental and economic damage (Unitar 2024).

E-waste, especially in the consumer electronics sector, has been growing every year with technological advancement and it has been changing the way we socialise, work and live (Baldé et al., 2024). As stated before, consumer electronics constitute of screens and monitors

with its waste representing 5.9 billion kg and small IT and telecommunications equipment, which represent 4.9 billion kg (ibid.). Nevertheless, only 25% of screens and monitors and 22% of IT equipment was formally collected and recycled. Compared to other categories of e-waste, consumer electronics is not the largest category of electronic waste. However, if consumption continues to increase, technology keeps progressing, producing electronics with short lifecycles and with limited repair options, and with poor e-waste management, these numbers will continue to grow exponentially (ibid.).

There is significant discrepancy in e-waste management across different continents. Europe, for example, in 2022 generated the most amount of e-waste per capita reaching 17.6kg per capita, but also had the highest collection and recycling rate, reaching 42.8% (Baldé et al., 2024). In contrast, the Americas generated 14.1 kg in the same year, but only 30% was formally collected and recycled.

Baldé et al. (2024) shows the existence of regional differences when it comes to e-waste generation and management which are linked to three main factors. First of all, the population's income level and buying power. There is a clear connection between the amount of e-waste a region produces and its purchasing power, meaning high-income regions tend to generate more waste since they consume more products and have more access to EEE. The second factor is e-waste legislation and laws. Countries which regulate and implement e-waste management regulations, with collection and recycling targets and policies have an average collection and recycling rate of 25%. Whereas countries that do not have these legally binding regulations, have an average of 0%. It is also visible in the disposal behaviour within citizens in different regions. In lower income countries there is more informal recycling, which cannot be considered environmentally sound, meaning that the official data does not comprise these numbers. Lastly, the maturity of e-waste management systems is a crucial factor to analyse. In countries which there is already a strong e-waste management system, have higher collection rates. However, it is important to keep in mind that informal recycling, although not always done in an environmentally sound manner, can also be advantageous for the overall effort.

Usually, the equipment with the highest weight are the ones with a higher collection rate, such as temperature exchange equipment (fridges, freezers, etc.) and large equipment (printers, dishwashers, etc.) (Baldé et al., 2024). One of the reasons for that is that, in some countries, suppliers might be required to do so when they sell or deliver new equipment. Another reason is that, because of its heavy weight and size, people are less likely to store them (ibid.). In terms of small IT and telecommunication products, as stated before, they have a higher collection and recycling rate than small equipment, for example (Baldé et al., 2024).

Perhaps because there are more countries that regulate such e-waste category or that this category has more valuable components and therefore, it is prioritized by e-waste management companies (ibid.). However, the collection rate is not as high as large equipment due to the personal data in small IT and telecommunication devices. People might be reluctant to give them away.

It is crucial to also note that beyond the e-waste that is collected and recycled, there is also the waste – namely 14 billion kg - that is improperly disposed in normal waste bins (Baldé et al., 2024). These are usually small IT and small devices that are discarded and treated as household waste, that usually ends up in landfills or incinerated (ibid.).

1.2.1.3 Environmental and health impacts of improper e-waste disposal

EEE comprises products with each causing different harm to human health and to the environment. To prevent that and to help recover secondary raw materials, there must be environmentally sound e-waste management systems (Rautela et al., 2021). There are several ways in which e-waste management impacts society and the environment, with not only direct but also spill-over effects and costs (ibid.). This consists of long-term effects faced by society coming from unmanaged hazardous substances and greenhouse gas emissions.

According to the Global E-waste Monitor 2024, due to the recycling of e-waste and the generation of secondary raw materials, 900 billion kilograms of ore extraction from primary mining was prevented, and 52 billion kilograms of CO2-equivalent emissions were averted (Baldé et al, 2024). This is due to urban mining, i.e. the resource extraction from waste instead of Earth's crust. This supports not only a reduction in mining but also hinders environmental degradation. Large-scale mining is a major source of water and air pollution, land degradation and biodiversity loss (Murthy et al., 2022). In terms of people's health, mining can increase respiratory diseases which are caused by the air pollution which is a consequence of the use of mercury to extract gold (ibid.). Beyond that, by not managing e-waste correctly there are several toxic substances that are released into the air (ibid).

E-waste, in general, contains toxic and strong substances, i.e. flame retardants, which are usually used in equipment containing plastics (Andeobu et al., 2023). Out of 17 billion kg of plastics in e-waste, 59 million kg contain this substance, and, out of these, 45 million kg are not managed correctly according to regulations (ibid.). These are mostly found in screens and monitors. Furthermore, it is a great challenge to recycle plastic containing flame retardants since the cost is too high to do so (ibid.). Besides that, the emissions caused by burning those substances as well as inhaling them are extremely harmful for both humans and the

environment. This is even more notable in low- and middle-income countries, where there are around 11 million informal workers dealing closely with e-waste (Baldé et al, 2024).

Another hazardous substance found in e-waste is mercury. Even though there are already ways to properly deal with it, it is a substance that is present in several EEE and specially on lamps. Another substantial problem is the incorrect management of temperature exchange equipment. These types of appliances contain refrigerants which, depending on type, can contribute to climate change and help exhausting the ozone layer. According to the Global E-Waste Monitor 2024, 73% of all temperature exchange equipment globally is managed improperly. In countries with no legislation, they are simply released into the atmosphere, and in other countries, with legislation, present a safe way to dispose and recycle, but fail to provide successful collection and management (ibid.).

Finally, there are countless unregulated exports of e-waste from high-income countries to low- and middle-income countries, which can then result in more emissions from both transport and waste handling (ibid.).

1.2.3 Regulatory frameworks and policies

In order to control the growing amount of e-waste and to protect the environment, effective regulations are crucial. Regulation fosters fair competition and promotes the environmentally responsible management of e-waste by ensuring proper practices in collection, transportation, sorting, depollution, dismantling, pre-treatment, handling of hazardous materials, and the export of components to advanced treatment facilities (Baldé et al, 2024). It is important to note that only 81 countries (out of 195) have regulations in place to manage electronic waste. And, in order for the collection activities of e-waste to be *formal*, it has to be in line with national e-waste legislation (ibid.).

1.2.3.1 Overview of e-waste regulations in the EU

The WEEE Directive (Directive 2002/96/EC) emerged based on the extended producer responsibility (EPR) principle making an obligation for EEE producers to collect and treat end-of-life products in an environmentally sound way (Shittu et al., 2021). Due to some problems and doubts between the member states, the Directive was revised and was replaced in 2014 by the Directive 2012/19/EU which is in place until today (ibid.).

As stated before, e-waste management in the EU is primarily regulated by the Waste Electrical and Electronic Equipment (WEEE) Directive – or Directive 2012/19/EU - and by the Restriction of Hazardous Substances Directive (RoHS). The WEEE Directive concerns the collection of all types of electronics and also establishes a target of a certain amount of e-waste that should be collected per year per capita (European Commission, 2012). Because this is an EU Directive, each member state is obliged to present different strategies to accomplish the WEEE Directive set targets (Shittu et al., 2021). The European Union (EU) is highlighted as a leader in WEEE management, particularly through this Directive, which sets high collection and recycling targets for member states (Kiddee et al., 2013).

The goal of the WEEE Directive is to enhance environmental performance across the entire lifecycle of electronics and contribute to sustainable production and consumption (European Commission, 2012). In sum, the WEEE Directive addresses the issue of growing amounts of e-waste. Some key components of the directive include the separate collection and proper treatment of electronic waste, setting targets for their collection, recovery and recycling; supports European countries tackle better the illegal waste exports by making it more difficult for exporters to do so; and reduce administrative burden by having a harmonised national EEE register and reporting format (ibid.). Furthermore, producers are responsible for the costs to manage e-waste, making sure they're properly collected and disposed of. This helps improve compliance amongst all member states (Baldé et al., 2024).

Beyond the WEEE Directive, there is also the Restriction of Hazardous Substances (RoHS) which complements the latter by limiting the use of certain hazardous materials in EEE (European Commission, 2012). The use of ten different hazardous substances is prohibited when manufacturing electronic products, with the most famous being lead and mercury (ibid.).

1.2.3.2 Extended Producer Responsibility (EPR) and its role in e-waste management

Out of 81 countries that have some kind of legislation or regulation that covers e-waste, 67also apply Extended Producer Responsibility (EPR) (Baldé et al., 2024). This is a policy measure which requires producers – or, in other cases, importers or distributors - to take responsibility, both financially and physically, for taking back their end-of-life products (ibid.). Consumers might return these products for them to either be reused, repaired, refurbished or recycle, all under producer's responsibility (Leclerc & Badami, 2019). This shifts the trouble from the government and consumers to the ones producing the equipment. EPR has not only been done with e-waste but also with waste from packaging, tires, batteries, etc. There are several

objectives that the EPR covers, focusing on different product life-cycle stages. These objectives include reduction in generation and disposal of waste, decreased hazardous materials in the waste stream, reduced reliance in virgin materials, lowered pollution in the product use phase and, increased focus on Design for the Environment (DfE) (ibid.).

There are multiple aspects stakeholders must take into account when it comes to designing EPR programs. Among these, scope of products, targets, quality of treatment and level of enforcement, allocation of physical responsibility and allocation of financial responsibility (ibid.). In relation to scope of products, there is a difference between the scope in one regulation to another, such as the EU covering a much broader variety of EEE than several North American e-waste program. Additionally, in some cases, regulators decide what are the quantities that need to be collected, handled and recycled. Occasionally, they can either enforce sanctions if producers do not reach their target or let the producers or their producer's association determine their own targets. When it comes to the quality of treatment, the regulators might have previously set and specific standards to how the e-waste is collected, recycled and disposed. Beyond that, to hinder environmental and health damages and ensure adequate e-waste treatment, regulators may decide on export restrictions according to the Basel Convention (UNEP, 1989). Additionally, e-waste might be required to be reused or refurbished before being recycled. Regarding the distribution of physical responsibility, it is the government's decision whether EoL equipment are collected directly by the producers or through a Producer Responsibility Organisation (PRO) or even different PROs, to escape monopolies. In contrast, when it comes to the financially responsibility there are several paths this could go. The regulations, most of the times, establish which stakeholder will take the financial burden. These costs might include the management of so-called orphaned waste or administration or research costs. Producers can choose if they pass these costs to the consumers or divide between them, with no effects on their revenue. In some cases, as opposed to handling the costs the producers themselves, some regulations allow for a fee on consumers, either visible or not, when the product is purchased or when returned (Leclerc & Badami, 2019). There are fixed costs per product category which can be modified by costs of recycling. In order for these costs to be paid accordingly, these might be decided according to the market share, enabling greater financial responsibility for the producers even if the physical responsibility continues to be collective. Another way to employ the fees is by either funding take-back initiatives or a mechanism of deposit-refund (ibid.).

In an effort to raise compliance and EPR efficacy, regulators might enforce other obligations. Producers might need to publish annual reports or invest in research and

development and awareness campaigns. There could also be municipal landfill bans imposed to producers. Additionally, they might be required to take back products or notify consumers about proper EoL management (ibid.). All in all, there are several variations that the EPR programs can have. However, as these programs are developed and executed in different regions, the regulatory burden on the industry also becomes more difficult. On top of that, there always conflicting interests between stakeholders in selecting what the best design for these programs is.

1.2.3.3 Challenges in e-waste management

E-waste management presents several challenges, due to the growing amount of e-waste generated worldwide and the complexity of materials used in the product's composition. As explained before, e-waste comprises a mixture of valuable materials such as gold and copper, together with hazardous substances such as mercury and lead. In order to properly handle and recycle these materials and to hinder the environmental impact, there is a need for sophisticated, innovative and modern technology. Nevertheless, without adequate recycling infrastructure and extensive informal recycling practices, the problem is only more aggravated (Sakhuja et al., 2021). Moreover, poor regulatory framework together with little public awareness results in the wrong disposal and recycling methods and, consequently, harms our health and the environment (Baldé et al., 2024).

The first challenge faced is the speed in which technology is changing and the growing amount of e-waste. Technology is developing so fast that it leads to product obsolescence, meaning people buy their equipment and rapidly change their devices for something new. Consequently, the amount of e-waste increases, making it almost impossible for the current e-waste management system to work (Ghulam et al., 2023).

Another challenge is the complexity of e-waste structure (Andeobu et al., 2023). The components of e-waste come from different materials containing plastics, metals, glass and hazardous chemicals, such as lead and mercury. Because these materials are so complex individually and altogether, it becomes more difficult for them to be sorted and recycled. Furthermore, some of these components are toxic and demand environmentally sound management in order to not be harmful for the planet and not pose health risks (Sakhuja et al., 2021).

Lastly, there is also a lack of appropriate legislation and enforcement (Baldé et al, 2024). Several countries lack regulations and/or have poor enforcement to deal with e-waste,

resulting in illegal disposal and unsound recycling practices. According to the Global E-waste Monitor 2024, as of 2023, 81 out of 143 countries had either policies and/or regulations concerning e-waste (ibid.). Nevertheless, it is crucial that there is constant enforcement and good quality of legislations. Currently, there are several legal instruments that fail to cover all different types of e-waste and do not define targets for collection and recycling. Even though, there is more target to enhance e-waste management from disposal to recycling, little attention and legislation is given to the preferred options, meaning reuse and prevention (ibid.). Besides that, there is growing problem of illegal trade of e-waste (Forti et al., 2018). It is often exported to developing countries where the waste can no longer be tracked. Beyond that, the labour and environmental regulations are less severe, leading to unethical and unsafe practices (Sakhuja et al., 2021).

In order to overcome these challenges, there is a need for alignment between stakeholders, those being government, producers and consumers, to promote more. Circular practices and reinforce regulations.

1.3 Digital Product Passports (DPPs): Concept and Implementation

1.3.1. Introduction to DPPs

An important step into facilitating the circular economy is the development of the Digital Product Passports (DPPs). They came as part of the Ecodesign for Sustainable Products Regulation (ESPR) which came into force on 24th July 2024. The ESPR is a result of the European Commission's commitment towards a more circular and sustainable products. It is a portion of a bigger package of measures that are crucial to achieve the goals of the 2020 Circular Economy Action Plan (European Commission, 2020). Beyond that, there is a growing number of other EU policies that will also rely on DPP, such as the Batteries Regulation, Detergents Regulation, Toys and Construction Products Regulation and the Critical Raw Materials Act (European Commission, 2024).

The goal of the ESPR is to mainly improve circularity and other sustainability aspects when it comes to products placed on the EU market by fostering more circular and sustainable business models and reinforcing resilience of the EU economy (ibid.). According to the European Commission (EC) a so-called sustainable product should use less energy, last longer,

be easily repaired and recycled, easily disassembled, should contain more recycled content and should have lower carbon footprint through its lifecycle.

It is important to note that the ESPR substitutes the current Ecodesign Directive 2009/125/EC and add to that by determining a framework with ecodesign requirements for specific product groups. The ecodesign requirements include: make products resource and energy-efficient; improve the durability, repairability and reusability of the product; handling the presence of materials that hinder circularity; improve the accessibility of information on product sustainability; make products easier to recycle and remanufacture; arrange rules on carbon footprint; and increase recycled content (ibid.).

The ESPR also introduced the DPP together with other two measures, those being Green Public Procurement (GPP) and rules to handle the destruction of unsold consumer products. The first measure relates to restructuring how public authorities spend on purchasing products, works and services in a way that promotes circularity and sustainability by allowing mandatory GPP criteria to be set by EU authorities who acquire the products they will regulate (ibid.). This is likely to increase the demand for sustainable products and, consequently, incentivize companies to invest in them. The second measure introduces a ban on unsold product destruction. It will demand companies to publish annual information such as the number of products discarded and why they did so.

Although DPPs are only now emerging in the policy world, there are already many examples of product passports examples in both regulatory and voluntary contexts. Some examples include material passports, Cradle-to-Cradle passports, smart labelling and Eco-labels. Even though they might have similar names, they are all significantly different given their scope and application to solve different problems (King et al., 2023). For that reason, they only collect and work with different data for different goals making it more difficult to come to a conclusion on which data must be in the product passport (ibid.).

1.3.1.1 What are DPPs?

As stated before, the DPP is an integral part of the Ecodesign for Sustainable Products Regulation by the European Commission (EC) and has originated as a solution to promote the transition towards a circular economy (WBCSD, 2023). The EC decided to implement the DPPs, at first in the European Single Market, as part of the EU Green Deal, to promote CE practices (Psarommatis & May, 2024). The goal is that, before products go to the market, they all have a DPP in which information over its entire lifecycle is provided.

A Digital Product Passport (DPP) is a data-sharing tool carried through a unique identifier (WBCSD, 2023). It shares product-related information across the entire supply chain that is necessary to enable product circularity. The system is backed by a decentralized information exchange system, which also secures the producer's intellectual property. The DPP can be updated and revised as soon as there is a change in the product concerning its composition, regulation, recycling, etc (CIRPASS, 2023).

The collection of data is accessible through electronic devices, and it has a 'predefined' range, access rights and agreed data management. This means that stakeholders from the entire value chain can access information about the product electronically (WBCSD 2023). The DPPs will, for the most part, facilitate access to information specific to certain products, related to circularity, sustainability and compliance (European Commission, 2024). Consequently, the data enables the DPP to encourage the production of sustainable products, help businesses and consumers make well-informed decisions and encourage the enforcement of the repair business model (WBCSD 2023).

According to the European Commission, the goal of the DPP is fivefold. Support sustainable production, enable the transition to circular economy, provide new business opportunities to economic actors, support consumers in making sustainable choices and allow authorities to verify compliance with legal obligations (European Commission, 2024).

1.3.1.2 Key components and functionalities

According to Jensen et al. (2023), there are seven crucial data clusters for a suitable DPP including product identification, usage and maintenance, products and materials, manuals and guidelines, supply chain and reverse logistics, environmental data and compliance. However, some authors consider that the data priority should be given to only product-related information which is provided by the manufacturer (Psarommatis & May, 2024). Therefore, when it comes to DPP implementation and effectiveness, there is a need for a more comprehensive framework (ibid.).

When it comes to DPPs main design features, there are two main components which are the DPP system and DPP data (ibid.). The DPP system concerns the *'how'* and is developed horizontally for all product groups (European Commission, 2024). It covers a searchable Web Portal, the DPP registry and the protocols and standards related to the IT architecture which are: unique identifiers; data links and carriers between the actual product and its digital representation; management of access permissions, information security and business

confidentiality; interoperability across technical, semantic and organizational aspects; data handling, data exchange protocols and data formats; data storage, archiving and persistence; data authentication, integrity and reliability; and lastly, APIs for managing DPP lifecycle and searchability (ibid.).

The DPP data, on the other hand, is the 'what' and is developed specifically for each product group. It concerns all information that will be included in the DPPs (ibid.). This information/data could be about technical performance, legal compliance, environmental sustainability performance, circularity aspects – durability and repairability -, and/or product-related information such as manuals, labels and instructions (ibid.). Having this information across the entire product lifecycle is crucial to assess a product's environmental impact. Having this information could simplify recycle, repair and reuse, giving the right stakeholders the correct information to further process the e-waste (Psarommatis & May, 2024).

The DPPs will be uniquely linked to a product and the data access will occur through a unique identifier inserted in a data carrier. Access to this DPP data is on a need-to-know basis, meaning there will be public and restricted data. Every product requires 4 unique identifiers, which are the product identifier, economic operator identifier, facility identifier and registration identifier - which is not public (ibid.). Beyond that, the DPP is based on a distributed/decentralized approach, integrating blockchain technology to do so. This means that it is much harder to manipulate data or have unauthorized access within the system, making it highly reliable (Circularise, n.d.).

1.3.2 Challenges and barriers

Although the DPPs come as a solution to the e-waste management problem, they also bring some challenges. There are namely three main challenges that relate to implementing DPPs, incorporating DPPs into current processes, data sensitivity and security, and the lack of a standard DPP version (Psarommatis & May, 2024).

Data security can become an obstacle since a lot of the information shared in the DPPs about the product is sensitive and confidential to the general public. Therefore, strong cybersecurity measures are needed to hinder misuse and unauthorized access (Langley et al., 2023). To address this problem the information needs to be encrypted, control mechanisms should have strict access and regular security audits should take place (ibid.).

Incorporating the DPP into current processes could also be a challenge. Some people might view DPPs as too complex or a financial burden. Great coordination and transparency

between stakeholders are needed in order to prevent that (ibid.). It is also important to note that, in order for the DPPs to work, all sections of the value chain apply the DPP. Without general adoption, the benefits of implementing the measure also decrease (ibid.).

All in all, DPPs are crucial for the future of manufacturing, underpinning their potential to catalyze a shift towards a more transparent, sustainable, and circular economy. However, there is a need for actionable guidelines and a methodological framework for industry-specific DPP development to assist manufacturers in adopting this innovative system, with a focus on overcoming practical challenges and barriers to DPP adoption (Psarommatis & May, 2024).

CHAPTER 2

METHODOLOGY

The goal of this research is to understand in what way Digital Product Passports (DPPs) can contribute to improving e-waste management and, at the same time, promote circular economy practices within the consumer electronics sector. To do so, this exploratory research investigates three different points of view: the one from those who develop the DPPs, the one from those who work at an e-waste management facility, more specifically, an e-waste recycler, and those who work in the consumer electronics industry, or industry experts. This chapter focuses on the choices related to the methodology that carried out this research.

Since this dissertation aims to gain detailed insights into stakeholders' perspectives, a qualitative research approach was chosen. More specifically, thematic analysis of in-depth interviews and reports were used to answer the research question. There is a mix of primary data collected through semi-structured interviews and secondary data gathered from reports produced by consultancy firms, climate institutes, and councils. This research method was the best choice to answer the research question specifically. The topic of DPPs and their relationship with e-waste management and CE is still evolving and is at an exploratory stage, making qualitative research more adequate (Creswell & Creswell, 2017). Furthermore, qualitative research allows me to better understand stakeholders' perceptions and experiences (Vaismoradi et al., 2016). By conducting interviews, more insights were gathered directly from the stakeholders to understand how they view DPPs in practice.

2.1 Data collection

As stated before, this research aims to understand how DPPs can contribute to improving e-waste management and promoting CE practices. To appropriately answer this question, both primary and secondary data were utilised. Two interviews were conducted to gather primary data, and secondary data was collected in three different reports.

2.1.1 Interviews

The interviews were conducted with a business developer at Eviden, a technology leader in trusted, data-driven, and sustainable digital transformation who offers DPPs as a solution, and the manager of technology, innovation, and business development at Coolrec, the division within Renewi that deals with e-waste. Both of these participants were selected because of their line of work.

The interview followed a semi-structured form (see Annex A), a data collection process in which there is a predetermined thematic framework, but it is not set in a specific order. Semi-structured interviews are mostly used in research as an exploratory instrument in which interviewees' answers can help progress the knowledge base for a topic. This is a common approach to understanding subjects' own perspectives (Kvale, 2011). Furthermore, unlike structured and unstructured interviews, where the interviews are entirely restricted or open, semi-structured interviews have the flexibility of creating a conversation between interviewer and interviewee (ibid.).

These interviews were steered by two different interview guides corresponding to the two interviewees. The guides had questions in standard as well as specific questions related to their line of work. The questions included themes such as current circular practices, limitations of DPPs, potential benefits of DPPs, impact of legislation on e-waste management and regulatory challenges, hazardous materials and cost of DPP implementation. The interviews were around 30 to 40 minutes, and they took place online on Microsoft Teams. The interviews were recorded, with the interviewee's consent, on the same platform and later downloaded and transcribed in order to perform the analysis.

2.1.2 Reports

Beyond that, existing data from three different reports were gathered. The first report (Report A) analysed was "Digital Product Passport: the ticket to achieving a climate neutral and circular European economy?" written by the Wuppertal Institute for Climate, Environment and Energy and the University of Cambridge Institute for Sustainability Leadership (CISL). The second report (Report B) from which the existing data was gathered was "The EU Digital Product Passport shapes the future of value chains: What it is and how to prepare now", written by World Business Council for Sustainable Development (WBCSD) and the Boston Consulting Group (BCG). Lastly, the third report (Report C) is called "Digital Product Passport as Enabler for the Circular Economy: Relevance and Practicability for Companies" and was written by

Dr. Adriana Neligan et al. from the Institut der deutschen Wirtschaft (IW), or the German Economic Institute.

These three reports were chosen and analysed since they provide a comprehensive overview of how DPPs can change e-waste management and enable a circular economy. Besides that, each of them offers complementary insights into the subject. The first report by Wuppertal Institute focuses on the role of DPPs in facilitating a circular economy in the EU. It underlines the benefits of employing DPPs in the electronics sector, including providing essential data for product lifecycle management, which can significantly reduce e-waste. The second report by the WBCSD and BCG focuses on how DPPs, especially in electronics, can improve transparency and collaborations within circular value chains. It emphasises the importance of DPPs in enabling recycling and repair and can help track product lifecycles, improving e-waste management. The third and last report by the IW focuses more on the practical implementation of DPPs and their importance to companies. It emphasises both the regulatory and technological requirements that businesses within certain sectors must meet to incorporate DPPs.

2.2 Data analysis

The interview transcripts, together with the three reports, were analysed by thematic analysis, which allowed to analyse the data closely and recognise different themes. By conducting a thematic analysis, not only will the direct effects of the DPPs on e-waste management be disclosed, but also the underlying challenges that could influence its adoption and performance.

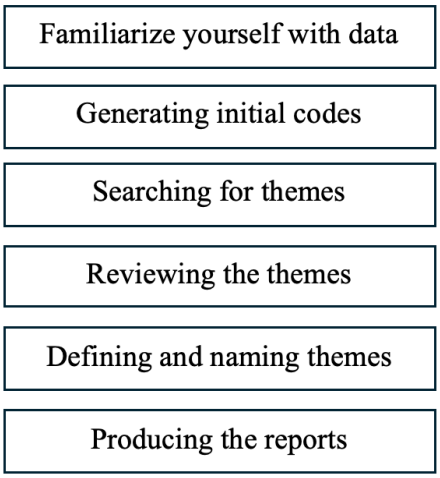
This research aims to answer the question of "How do Digital Product Passports (DPPs) contribute to improving e-waste management and promoting circular economy practices within the consumer electronics sector?" and, therefore, indicates the need to explore patterns and themes emerging from the data. More detailed and refined perspectives from different stakeholders, such as manufacturers, DPP developers, and recyclers, could be captured through the interviews and reports. Furthermore, thematic analysis is considered a more flexible approach and works well with both interview transcripts and report secondary data. The deductive approach of the thematic analysis implies looking at the data with some preconceived themes already based on the theoretical framework. More importantly, the thematic analysis allowed me to extract relevant themes in practice, which is crucial when understanding DPPs and their actual impact on e-waste and the circular economy. Lastly, employing thematic

analysis to analyse the interviews with stakeholders in e-waste management can highlight potential opportunities and barriers to DPP implementation and success.

The thematic analysis followed a six-step approach, as shown in Figure 2, including familiarisation, coding, generating themes, reviewing these themes, defining and naming themes and documenting them (Braun & Clarke, 2006). Firstly, a familiarisation with all the collected data was achieved, including transcribing the interviews, reading the reports, and taking initial notes. Second, with the help of the software Atlas.ti, certain sections were highlighted, and labels or codes were identified to explain their subject. After that, from the codes the identification of patterns among the codes was created and, consequently, the generation of themes was conducted. The codes were combined into different themes according to the research goal. After that, the themes were thoroughly reviewed, and decision was made on which themes were helpful and which were not and if they really represented the data or not. After the last theme review was made, each theme was named and defined to make it as succinct as possible to move on with the research.

The eight final themes that emerged from the thematic analysis included transparency and traceability in the product lifecycle, DPP usefulness in recycling, potential benefits of DPPs in reuse and repair, limitations of DPPs, regulatory challenges, lifecycle data and circularity, extended product life and resource efficiency.

Figure 2 - 6-step Thematic Analysis



Adapted from: Virginia Clarke & Victoria Braun

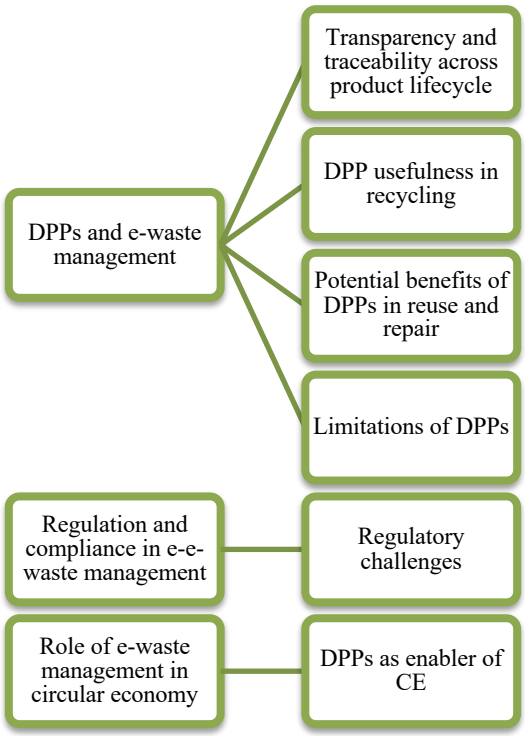
CHAPTER 3

RESULTS

This chapter will introduce the eight most relevant themes that emerged from the thematic analysis of two interviews and three reports. Each theme will be presented and explained using examples from the interviews and report insights. These findings will help clarify how DPPs contribute to improving e-waste management and promoting circular economy practices within the consumer electronics sector. The analysis uncovered eight themes, which will be discussed in more detail below.

As shown in Figure 3, the themes that emerged from the analysis are (1) transparency and traceability in the product lifecycle, (2) DPP usefulness in recycling, (3) potential benefits of DPPs in reuse and repair, (4) limitations of DPPs, (5) regulatory challenges, (6) lifecycle data and circularity (7) extended product life and resource efficiency. Each of the emerging themes will be thoroughly explained in the following sections, and so will the sub-themes related to them.

Figure 3 - Themes emerged from the thematic analysis



3.1 DPPs and e-waste management

3.1.1 Transparency and traceability in product lifecycle

This theme focuses on how DPPs facilitate the traceability of materials and components in the consumer electronics industry, eventually enhancing e-waste management. It is unanimous between the interviewees and reports that the DPPs will assist with product and material traceability and transparency. Interviewee 2 explained: "DPPs help with tracking not only the origin but also the composition of materials, ensuring that these components can be recycled or reused". He then added that the DPPs not only help the transparency in the VC but also provide security for companies' data. This is due to their decentralized blockchain technology, which is the safest it could be.

Report B goes on stating that there is, currently, no tracking of resources, lifestyle extension and EoL activities. This shows the current lack of transparency and VC collaboration. Therefore, the DPP has the potential to make products' environmental impact visible and traceable but also simply accessible to all stakeholders in the VC. According to Report B, "This will increase transparency and circular VC collaboration that facilitate circular designs (e.g., designs for recyclability) and closed-loop activities (e.g., repair, refurbishment, recycling)". Similarly, Report A confirms and states that DPPs also have the capacity to provide extra layers of reliable product information, such as raw materials and recycled content. This could also help with transparency in the future when improvements are happening in products' circular design.

However, they also emphasize that transparency of information as business confidentiality needs to be maintained through the supply of different access levels. It is a common concern regarding how to determine the criteria for DPPs. According to Report B, some stakeholders questioned themselves on how to determine if other stakeholders in the VC' need to know certain information and what commercially sensitive information can be protected. They go on to say: "However, such arguments should not be used as an excuse for not having to disclose elements such as hazardous substances in a product". They conclude that an approach with layered access would be ideal for dealing with sensitive information and could help address the transparency-confidentiality dilemma.

As stated before, electronics will be one of the prioritized industries for DPP implementation. Even though there are already regulations in place (WEEE Directive) that deal with e-waste, e-waste is currently the fastest-growing waste stream in the world, with an incredibly low recycling rate. According to Report B, "Enhanced transparency via DPPs can enable greater

access to the USD $57 billion material value stored in e-waste". However, this all depends on how the data is shared across the VC.

Regarding the traceability of electronics, there are two main concerns brought about by Report B. First of all, it is clear that, in the short term, it is more likely that there will be more impact in the upstream than in the downstream (collectors, recyclers, etc.) and improving disassembly and recycling of electronics. According to them, "This is because tracking parts and components will be difficult once the device is disassembled and many EoL operators currently work in large bulks and with standardized processes for electronics regardless of brand or model". Consequently, the traceability will be lost after the product's use phase.

This theme directly aligns with the research question by showing how DPPs can contribute to more efficient e-waste management since they facilitate the traceability and recognition of materials across the entire VC.

3.1.2 DPP usefulness in recycling

This theme focuses on the DPPs' usefulness in the recycling sector. On the one hand, Reports A, B, and C have similar ideas about DPPs' usefulness in recycling. According to the authors of Report B, recycling is one of the ways to improve the circularity of resources. DPPs could be made visible and traceable for all actors in the value chain (VC) products' environmental impact. According to them: "This will increase transparency and circular VC collaboration that facilitate circular designs (e.g., designs for recyclability) and closed-loop activities (e.g., repair, refurbishment, recycling)". They go beyond that, stating that electronics have the most significant waste footprint, with a laptop's waste footprint being 400 times higher than its own weight. "Beyond that, most electronic devices are complex products that, at scale, contain large amounts of valuable and scarce raw materials, some of which are hazardous if not appropriately recycled". They state that there is a lack of information on the EoL activities, such as tracking the recycling rates to provide full recyclability potential for appliances. Therefore, the DPPs will be a new and better way to share data across global value chains.

According to Report B, recyclers, collectors, and disassemblers play a pivotal role in retrieving valuable materials from electronic waste. However, they state that in the short term, there will be more impact on the upstream, by facilitating communication and collaboration between stakeholders in the VC instead of actually improving the recycling of electronics. In their words: "This is because tracking parts and components will be difficult once the device is

disassembled and many EoL operators currently work in large bulks and with standardized processes for electronics regardless of brand or model". This goes hand in hand with what was stated by Interviewee 1, who works at a recycling facility when he states that it is too difficult to scan products when they arrive at the recycling centre since they come in bulk in a container and not one by one. In his words: "If there is a way of scanning these digital passports automatically and getting that information back in an automatic way, then for the recycler, this would work better, with some kind of automated sorting".

According to Report A and similarly to Report B, DPPs have several benefits including knowing whether a product can be recycled and how to recycle it. In report A is stated: "As a tool to provide the underlying factual information required to substantiate sustainability claims, DPPs could form a basis for creating green markets". For them, recyclers should have more details into disassembling products and how the parts can be recycled. Furthermore, in order for the DPPs to also be effective for recyclers, there is a need for consistent and reliable information.

On the other hand, Interviewee 1 highlighted his concerns about the usefulness of DPPs in the recycling sector. He emphasizes that, even though DPPs are somewhat a new topic, there were conversations and meetings in the European Commission 10 years ago, talking about not DPP as we know it but a similar idea. He noted: "So, I think it is in terms of preparing for reuse and parts harvesting it could be useful, but as of now it has too many limitations, at least in the way that it is going to be set up now, and that people are thinking of setting it up now".

He adds that another problem is when it comes to DPPs in the recycling sector. "We still get today, at least one to two fridges per year, which date from before the Second World War. They probably have not worked for years anymore, but we still get them in. So how do you keep then that information in that digital passport up to date?". Therefore, according to him, it is challenging when it comes to older appliances because there is no data, only what was told to recyclers. There might be hazardous substances that were acceptable at the time of the appliance and now have to be treated differently.

3.1.3 Potential benefits of DPPs in reuse and repair

This theme focuses on the potential benefits of DPPs in the reuse and repair of electronic products. According to Report C, one of the ecodesign content requirements of the DPPs are "Durability, reliability, reusability, retrofittability, repairability, ease of maintenance and refurbishment". However, they also state that the issue of repairability is also being pressured

by the EU Right to Repair, which will make information about repair and maintenance necessary. "The aim is to make it easier and cheaper to repair goods.".

Similarly, Interviewee 1 states that DPPs could be useful for preparing and harvesting parts for reuse. However, when talking about reuse, people always have to think about the second-hand value of the product. He continues: "What is the second-hand value of the appliance? Because you have to take the appliance, you have to test it, you have to clean it, and potentially you have to repair it". He explains that 150 to 200 euros in the EU go straight to salary costs and, therefore, the second-hand value must be greater than that. "So that makes sense for a high-end washing machine. For instance, it does not make sense for a 25-euro coffee machine".

Interviewee 1 explained his continuous work with their reuse partners, one step before them (recyclers), and how they would probably be helped with DPPs. "I know the way they're working, and today they rely a lot on information and training they get from producers so they can repair one brand, but they can't repair the other one because they don't get the information". Thus, with the use of DPPs, they would be able to get much more information than they are getting today and would be able to bring back many more appliances to the market than they do today.

Another important note by Interviewee 1 is that it would help workers in the reuse stage of the value chain and consumers who would like to repair their products. He jokes, "I found out that replacing the screen of a smartphone isn't that complicated, if only you find out how to do it. YouTube can be your best friend".

According to Report B, repair, refurbishing, and take-back options are still evolving and often require more data and information. They state, "This highlights the critical need for leveraging data via the DPP to enable transparency and collaboration among VC actors to improve product design and environmental performance".

3.1.4 Limitations of DPPs

An important theme that emerged from the data is regarding the limitation of DPPs. Interviewer 1 emphasizes that he is sceptical about the usefulness of DPPs, especially for recycling, as was previously stated in a previous theme. This is due to two main factors, those being the challenges in keeping the appliances' data updated and the problem of ensuring that the data is coming from all steps in the VC is accurate. Regarding the first challenge, he states that many companies do not remember certain materials or components of products they sold prior.

Consequently, they might upload wrongful information in the passports. According to him, it is also difficult to access reliable information about materials and components in older appliances and, as we know these appliances will not get DPPs.

Another limitation, according to Interviewee 1, is that all appliances arriving at the recycling centre come in bulk rather than one by one. This makes it impossible for these facilities to scan DPPs from hundreds of products simultaneously. Unless there would be an automated process capable of scanning all DPPs simultaneously. He concludes: "And then, what happens? The average appliance, when it goes to recycling, apart from fridges, has a longer lifetime, but the average appliance is five to seven years. I mean, if tomorrow the new iPhone comes out, then the day after tomorrow we have the first one in our facilities. That's how simple it is.".

Another limitation of the DPPs is regarding hazardous substances. According to Interviewee 1, if the information on DPPs is accurate and up-to-date and if it was less costly to implement DPPs, it would be helpful to have information on the hazardous substances in electronics. He states: "Today, if you look at the European legislation alone, there is more than 600 substances that are regulated and that are relevant in electronic waste". The problem is regarding old appliances that contain hazardous substances, and that will not get a DPP. For him, the problem is that substances that are okay today might be hazardous in 10 years.

3.2 Regulation and DPPs

3.2.1 Regulatory challenges

This theme will primarily focus on the regulatory challenges or difficulties industries and businesses face implementing DPPs. Four main challenges emerged here, between reports and interviews. The first challenge is regarding company size and the fact that it will be too costly to implement DPPs across the entire VC. Report C and Report B state that many small and medium-sized enterprises (SMEs) are not yet fully digitalized, and because their data is not digitally collected or stored, it will be too costly and complicated to change that for the DPPs fully. Report B states: "Although it ensures clear expectations, streamlined implementation and full transparency for all VC actors, it could overburden SMEs and thus slow down implementation". This goes hand in hand with the concern of Interviewee 1, but more focused in the downstream of the VC. According to him, it is too costly for a recycling company to implement DPPs: "I always say it's perfectly okay, that we can use it (DPP) if regulators absolutely want us to do it, but someone will have to pay that, because we're not a nonprofit

industry. We actually need to make a profit, and in the end, that will then be the consumer. He goes on explaining that if we would have the choice between two phones, would one be willing to pay 100 euros extra just because that phone has better information to the recycler? Or has recycled content? He states: "No, it would have to be the same cost".

Interviewee 2 agrees that the cost of DPPs might hinder its implementation. However, he believes that worldwide economic uncertainties, such as wars and market turndowns, are already preventing their clients' optimism about the DPPs. He states: 'We talk to clients, it's always 'Okay, can we avoid that act or that regulation? And if not, can we do it with Excel? Because it's cheaper to just hire someone to shift Excel sheets than to include a new, innovative product.'. Therefore, businesses are more likely to go for the cheaper and familiar way, instead of implementing something completely new. He concludes by saying that, in order to overcome that, businesses need a clear return on investment (ROI) to overcome this hesitation.

Across Reports A, B and C, issues concerning standardizations of DPPs also arose. They all emphasize the need for a standardized, cross-sectoral DPP framework for both mandatory and voluntary information to guarantee consistent implementation across all industries. As stated in Report B: "DPPs should enable a common framework for additional voluntary product information sharing, by setting a standardized approach to exchange information such as recycled content or carbon and product footprints in complex supply chains". Report C adds to that: "By creating an infrastructure (DPP system) for the DPP that is flexible enough to accommodate cross-sector and cross-system information and at the same time specific enough to comply with concrete requirements for relevant sectors, standards and norms can be integrated into the structure of the DPP".

Another concern and related to having a standard DPP framework, is regarding interoperability. Report C states, "Interoperability refers to the ability of different systems, techniques or organizations to interact". This means that it is crucial for all sectors and industries in the VC to communicate effectively through different systems, which is necessary for consistent product data sharing. They go on to state that: "Overall, however, only 21 per cent of the 1,051 companies surveyed from industry and industry-related service providers hand over data to other companies at all". This brings us to another challenge which is the overall concerns regarding data security and copyright. "Legal concerns regarding data privacy, copyright and/or antitrust law are a reason for 64 per cent of companies not to hand over any data, or not to hand over even more data". They all emphasize the need to protect sensitive business information and product data. Report C notes that balancing data security and transparency is critical to overcoming this challenge. Within the same subject and when asked

about the DPP solution provided by their company, Interviewee 2 states that transparency is crucial. He continues: "But what we are selling as well is security". He explains that, because of the secure and decentralized nature of the blockchain technology, which is used by Eviden, it would be extremely difficult, almost impossible for a data breach to happen.

Lastly, Report B emphasizes the need for companies to engage and contribute to DPP discussions to help shape the future of the regulation. According to Report B, "Business perspective and knowledge is important to ensure that the DPP will not become a bureaucratic burden but a useful tool for increased transparency". Beyond companies, Report B also states the need for all relevant stakeholders in the VC to help set these industry standards in order to fill the regulatory gaps.

3.3 DPPs and circular economy

3.3.1 Lifecycle data and circularity

This theme emerged from the thematic analysis regarding how product lifecycle extension, with DPPs as a tool, can enable a circular economy. According to Reports A, B, and C, as explained before, the DPPs have been established as an essential tool for gathering and sharing product lifecycle information. This information goes from product design to production to recycling and disposal and, thus, supports circular economy strategies. According to Report B: "As proposed by the EC, DPPs should serve as a key tool to create transparency on products, thereby promoting the transition to the circular economy and supporting economic growth". All reports find it essential to make the data on the product's durability, repairability and recyclability available and accessible to all consumers.

Consequently, this promotes circular practices such as user maintenance, reuse and recycling, enabling circular economy models. As Report A notes, "The creation of a fully functioning digital circular economy information system must be considered a crucial prerequisite for improved resource efficiency and effectiveness". Similarly, Interviewees 1 and 2 also believe DPPs, providing product lifecycle information if up to date, can enable the circular economy.

Furthermore, ensuring all product lifecycle information is available also promotes transparency across the entire product lifecycle. According to Report A, "Such information exchange will provide key knowledge for future circular economy strategies and set the necessary level of transparency". They believe it is important that the stakeholders provide product information on the origin, structure and environmental impact. The DPPs are able to

do that and enable better tracking of materials and improve transparency between stakeholders. In addition to that, the DPPs can help ensure traceability which is crucial for enhancing recycling, repair and refurbishment and EoL. However, as Report A states, it is crucial to remember that DPPs enable recycling and other circular economy activities such as repair and refurbishment. Beyond that, it also helps with decarbonization efforts and how DPPs could facilitate that and carbon reporting.

Report C goes deeper and states that digital data management is crucial in enhancing circularity. Thus, it is not only sharing information but sharing information digitally. They state: "Actors along the value chain must be able to communicate efficiently – and thus automatically - via interfaces to be able to transmit relevant information without losses and in a resource-saving manner". They go on to explain that: "As digitalization increases, datasets become interconnected, and environmental impact assessments are required throughout the product lifecycle, legislation for different product categories is becoming increasingly interconnected". According to Report B, "Additional ways to increase circularity include circular business models and design as well as extending products' lifespans through practices such as enhanced use, reuse, repair, repurpose, etc., which could be enabled by quality data and information".

Although Interviewee 2 agrees that DPPs can promote circular economy through extending product lifecycle, he states his concerns on consumer behavior. He points out that consumers often choose their products by price and not by their circular characteristics and the amount of CO2 emitted to produce it. He states: ‘Then it depends on the end consumer... if you think about someone who is buying from Temu, they buy that because...it's cheaper […] they don't care about sustainability. According to him, it always depends on the end consumer, the company’s standard and what they want to sell to the end consumers.

3.3.2 Extended product lifespan and resource efficiency

This final theme focuses on how DPPs help extend product life and promote resource efficiency. All reports state the importance of the role of resource efficiency and extended product lifespan. All reports agree that DPPs can help enhance product lifespan by supplying consumers and professionals with the correct data for reuse and repair purposes. This allows consumers to keep their products for longer and reduce waste. According to Report B, the DPPs have the opportunity to allow easier access to product data, allowing both consumers and repair professionals to repair their products. "While repair and take-back options are evolving, they

are still nascent, often lacking the required data and information. This highlights the critical need for leveraging data via the DPP to enable transparency and collaboration among VC actors to improve product design and environmental performance". Similarly, according to Reports A and C, one of the strategies the DPPs could support is regarding data for repair and predictive maintenance. This can help extend the product's lifespan by tackling problems before the product breaks down. Furthermore, the data gathered by DPPs enables consumers to plan repairs more efficiently, avoiding early product disposal. According to Report A, "DPPs could be a big step forward for more sustainable products and consumption, boosting energy and resource efficiency by enabling new business models based on e.g. digital data sharing".

Beyond facilitating maintenance and repairs, both Report B and Report A consider that DPPs can help reduce the need for raw materials by extending products' lifespan. This would contribute to resource efficiency since products would be kept in use for longer, either through repair or refurbishment by the consumers themselves or by repair professionals. Consequently, less energy and materials are needed. As Report B states: "Leveraging the transparency that the DPP can create for improving circularity will not only open up additional value potential for companies but also enable utilizing already extracted resources more efficiently to achieve less wasteful consumption within planetary boundaries". Report A concurs when talking about all the benefits DPPs could bring: "Another overarching benefit of DPPs would be their enabling role for resource optimization and also for increasing energy efficiency via circular economy practices throughout the entire value chain".

This goes hand in hand with the topic of circular design and design for longevity, since having a more circular design allows for product lifespan extension and resource efficiency. All reports agree that DPPs can motivate manufacturers to make products more accessible to repair and to adopt CE principles. Thus, design for longevity is noted as essential to enhancing resource efficiency and promoting circularity. According to Report B, "Companies can use the obtained transparency to create more circular products and reduce waste and resource consumption.". Report B goes on to state that when it comes to electronics, brands will likely be affected by DPP implementation since they play a crucial role in electronics VC. "With much of electronics' energy impact coming from production and large amounts of e-waste piling up once the devices are disposed of, brands could have a great impact by changing their approach to product design and circularity.". They go on by giving a vital example when it comes to tablets: "For tablets, for example, approximately 72% of their total energy impact is coming from the production phase of their lifecycle, 8 where brands could have a significant impact on potential reductions.".

CHAPTER 4

DISCUSSION

This section will discuss the literature and results from the data analysis. It is essential to reflect on the objective of this dissertation, which is to shed light on how DPPs can contribute to improving e-waste management and promoting circular economy practices within the consumer electronics sector. After analysing the data through a thematic analysis, seven themes were discovered as seen above. The idea here is to analyse the thematic analysis results and connect it to the literature. To go deeper, the objective of this research was twofold. First, to provide a comprehensive understanding of DPPs and their functionality, implementation and significance in the consumer electronics sector. It will also analyse critical features and mechanisms behind DPPs and regulatory challenges. Second, the role of the DPPs in promoting circular economy practices within the consumer electronics sector should be assessed.

To make it easier for the reader, this discussion will be divided into four parts. First, a summary of the key findings will be provided. Then, it will be discussed the benefits of the DPPs to enhancing e-waste management. Thirdly, the challenges and barriers to DPP implementation will be provided and analysed with the literature. And, lastly, an explanation of how DPPs can promote circular economy practices will be given.

The results indicate that DPPs can considerably enhance e-waste management and promote circular economy practices in the consumer electronics sector. This could be accomplished by means of improved transparency, collaboration and traceability across the entire VC. The DPPs offer crucial material and product data as well as recycling options, repairability and reuse information, thus encouraging circular designs and prolonging products' lifespans. Although DPPs are still highly beneficial in reducing extraction of raw materials and facilitating reuse, some challenges persist such as processing of products in bulk, implementation costs and figuring out the balance between transparency and business data confidentiality. In order to promote more sustainable and resource-efficient practices, these challenges must be overcome.

4.1 DPPs and e-waste management

4.1.1 Transparency and traceability in product lifecycle

According to the literature, DPPs have emerged as a great way to enhance how e-waste is managed today. In this section, three different themes from the results section will be discussed: transparency and traceability in product lifecycle, DPP usefulness in recycling and potential benefits of DPPs in reuse and repair. The first theme that emerged from the analysis was transparency and traceability in the product lifecycle. According to the results and, similarly, with the literature reviewed (e.g Psarommatis & May, 2024), DPPs can definitely enhance transparency and traceability across electronic value chains. Currently, there is no way to track resources, life extension and EoL activities across the entire VC, showing a lack of transparency and collaboration. As one of the interviewees explained, DPPs will help track the origin and composition of materials, ensuring the recyclability or reuse of these components. Furthermore, it was also shown that DPPs can provide other types of reliable information, such as recycled content or raw materials, enhancing transparency across the VC even more. Therefore, the DPPs could fill the existing gap regarding transparency across the VC and appear as a significantly valuable tool for enhancing the way e-waste management is now done.

Complementing what was mentioned by Walden et al. (2021), it is also known that DPPs for electronics will be one of the first product industries for its implementation. According to one of the reports, increased transparency via the DPPs can enable better access to the excellent material value present in e-waste, depending on how the data is shared across the VC. Besides DPPs increasing data transparency, they also increase circular practices such as circular design in order to make products more accessible to recycle, for example, or closed-loop activities such as providing information to help repair and refurbish. However, according to one of the interviewees, business confidentiality should be maintained at all costs when it comes to transparency of information. It is a concern among businesses that the entire value chain could access their products' confidential information. In order to protect sensitive information, different data access levels should be supplied between stakeholders in the VC. It is crucial to determine which information can be accessed by which stakeholder. Thus, the transparency-confidentiality dilemma would be solved.

Lastly, the thematic analysis also noted that, in the short term, the DPPs will have more impact in the upstream instead of the downstream, meaning collectors and recyclers. This is because once the products are disassembled, it becomes more difficult to track their parts since

they usually work with large quantities of appliances. Consequently, they lose the traceability of products.

Therefore, the DPPs enhance e-waste management by allowing more transparency and traceability in the product lifecycle. It is essential, however, to keep in mind that information reaching the downstream of the VC is as important as reaching the upstream, and it should be taken into account.

4.1.2 DPP usefulness in recycling

Another important topic that arose from the data analysis was regarding the usefulness of DPPs to recycling. According to the ESPR, one of the requirements include making products that are easier to recycle and increase the recycled content (European Commission, 2024). However, when researching literature about DPPs, little attention was given to the downstream of the VC, e.g. e-waste collectors and recyclers.

Consumer electronics are primarily produced on a larger scale and designed for fast obsolescence for different reasons. A vital issue connected to these appliances is the low recyclability rate. This is due to numerous products being difficult to disassemble and/or containing hazardous substances, which limits their recyclability (Meloni et al., 2019). Consequently, when a product reaches its EoL, it is usually disposed of in landfills or incinerated instead of being recycled. This leads to several valuable materials being lost and to more material extraction (ibid.).

Considering these challenges, the DPPs are drawing attention in the recycling sector. According to Psarommatis & May (2024), data-rich tools such as the DPPs can improve recyclability rates by providing information to consumers on where to dispose of their appliances for better recycling rates and to collectors and recyclers by providing information on hazardous substances present in the products.

Despite the advantages, some practical concerns have been raised by recyclers. According to Report B, even though recyclers play a crucial role in retrieving valuable material from e-waste, in the short term, the DPPs will impact the manufacturers more than the recyclers. The main concern of recyclers is the difficulty of scanning appliances arriving at the recycling centre in bulk. According to Interviewee 1, the only way to avoid this problem would be to have an automated system in which all appliances could be scanned at the same time when they arrive at the facility. If not done this way, the DPPs will become obsolete for those

working as e-waste recyclers. This is a concern that is not addressed as much in the literature since more attention is given to businesses that produce electronic appliances.

Therefore, although data-sharing tools such as the DPPs are understood to improve recyclability rate by providing information to all stakeholders in the VC, there are still practical difficulties that those in the downstream of the VC might face.

4.1.3 Potential benefits of DPPs in reuse and repair

The DPPs have great potential to promote reuse and repairability by providing data on how to repair products yourself and where to bring the product if it needs repair and, consequently, extending the products' lifecycle. It is an ecodesign requirement for DPPs to have information on durability, reusability, repairability, and refurbishment. Beyond that, there are also new measures regarding the European Commission's Right to Repair, which proposes that more products can be repaired within legal guarantee but also that consumers have more manageable and cheaper options for repairability.

DPPs could be extremely useful when preparing electronics for reuse. However, it is important to remember the product's second-hand value. As Interviewee 1 states, and from the perspective of someone who works in the recycling sector, because certain electronics are already so cheap and it takes labour and new parts – meaning money - to repair it, they have to think if it makes sense to do so.

It is also important to note that those working in the reuse sector rely greatly on information from manufacturers. This allows them to repair products without mistakes. Implementing DPPs would allow them to get much more information, and therefore, they would be able to repair more electronics and bring them back to the market.

Lastly, as stated by one of the interviewees, the DPPs are not only beneficial for repair workers and manufacturers, but also for consumers who will now have the instructions allowing them to repair their own electronic devices – if possible. This is important due to the fact that many people do not bring their electronics to repair because repair facilities are too far away or because they just cannot transport there. With the DPPs, more appliances can be repaired and, often, could be costless.

4.2 Challenges and barriers to DPP implementation

Even though DPPs can enhance e-waste management, there are also some challenges and barriers to its implementation. According to the literature, implementing them has three main

challenges: incorporating DPPs into current processes, data sensitivity and security, and the lack of a standard DPP version (Psarommatis & May, 2024).

The research confirmed the first challenge regarding incorporating the DPPs into already existing systems. According to the literature, this could be a problem as some people and businesses view DPPs as too complex and as a financial burden. This is in line with the data analysis results and the fact that small and medium-sized enterprises (SMEs) are not all fully digitalised and/or have their own system, making it too much of a burden to incorporate DPPs into their systems. Besides that, it will be too costly to implement DPPs across the entire VC. Report C states, "Although the DPPs ensure clear expectations, streamlined implementation and full transparency for all VC actors, it could overburden SMEs and thus slow down implementation.". Interviewee 1 also agrees with that challenge and states that if regulators absolutely want them to implement DPPs, they will do it, but someone else must pay for it. This goes hand in hand with the challenge of interoperability, which refers to the ability of different systems and organisations to interact. According to one of the reports, it is important that all stakeholders in the VC can communicate perfectly across the different systems they use. This allows for consistent product data sharing.

Regarding data sensitivity, both the literature and the data align (e.g. Langley et al., 2023). Because a lot of product information shared in the DPPs is confidential, there should be strong cybersecurity measures to make sure they are not misused and accessed by unauthorised people. This topic was also brought up by Interviewee 2 since they developed the DPPs. Although this might seem an obstacle, he explains that, because of the secure and decentralised nature of the blockchain technology, which is used by most, if not all, DPP developers, it would be challenging, almost impossible, for a data breach to happen.

Another limitation that arose from the data analysis and that was not found in the literature was the fact that many times, the appliance data could be outdated and/or the data might not be coming from all stakeholders in the VC. This could directly and negatively impact recycling, for example, as one of the interviews stated. According to him, a lot of the time, companies do not remember certain components of products they sold years before or old appliances do not have DPPs and will not, therefore, have any data.

Besides that, the fact that all products arrive in bulk at the recycling facility could also be posed as a limitation of the DPPs. This is due to the fact that there is no time to individually scan each DPP before proceeding to the mechanical recycling. According to one Interviewee, unless there is an automated process that scans the DPPs all at once, the role of the DPPs becomes obsolete for the recycling sector. He continues to provide another limitation connected

to the DPPs, which is regarding hazardous substances. He states that the recycling facility still receives appliances that were manufactured before the Second World War and, therefore, no DPP will help by offering the data. He also states the importance of having data that is up to date since hazardous substances contained in electronics change constantly.

Both the literature and the data align when it comes to the actual architecture of the DPP (e.g. Langley et al., 2023), and the need for a standard version (e.g. Walden et al., 2021). They all stress the need for a cross-sectoral, standardised DPP framework for mandatory and voluntary information to guarantee consistent implementation across all industries, not just electronics. This DPP architecture should be flexible enough to have cross-sector and cross-system information but also specific enough to comply with requirements for different standards and sectors.

Therefore, there are nine main challenges and barriers to DPP implementation, namely incorporating DPPs into existing systems, cost of implementation, interoperability issues, data sensitivity, outdated/incomplete product data, arrival of products in bulk, lack of DPPs for older products, hazardous substances and outdated data and, finally, lack of a standardised DPP version. These challenges highlight different financial, technical and logistical aspects that could hinder the general adoption of the DPPs in the future.

4.3 DPPs and circular economy

DPPs play an essential role in supporting and promoting CE practices by providing appropriate data to prolong products' lifespan, allowing for data transparency and product traceability across the entire VC, allowing for new circular business models to appear (e.g. take-back and repair models) and reducing material use. In order to have a better and deeper understanding of how DPPs can support CE practices, the four flows and the 8 Key Element Framework will be employed. That way, it will be possible to understand precisely in which CE practices the DPPs directly connect to. According to the literature, CE should be understood as an economic model focused primarily on eliminating waste, maximising resource use and rejuvenating natural systems (Circle Economy, 2024). According to the Circle Economy Foundation (2024), it is based on four main principles, also known as key flows. Within these principles, there are eight core and enabling elements of circularity that serve as a conceptual framework.

When it comes to transparency and traceability in the product lifecycle, two main principles stand out. First of all, the DPPs enable transparency across the entire VC, allowing

stakeholders to access the components of products. This aligns with the CE principle of *narrow flows*, by making sure fewer resources are used and less waste is produced. The DPPs emerge as an important tool to make sure stakeholders identify both the source and composition of materials, allowing them to have a better understanding of the product and material recovery. More than that, the DPPs also contribute to *cycle flows*, meaning that more materials and products can be reused at their EoL, generating a circular flow of resources. By allowing product data transparency, the DPPs allow better collection and reprocessing of material. Beyond that, it can push manufacturers to design products for recyclability and disassembly, thus facilitating both reuse and recycling and ensuring efficient resource use throughout their lifecycle.

According to this understanding and connecting to the transparency of information provided by the DPPs, one main CE key element directly relates to and should be addressed. *Incorporate digital technology* is crucial for a thriving circular economy. According to the literature, incorporating digital technology enables tracking and optimisation of resource use, reinforcing the connection between VC stakeholders and the implementation of circular models (Circle Economy, 2021). DPPs, therefore, come as a way to incorporate digital technology to address the lack of and incomplete information about certain electronics. They allow for all stakeholders to share product information and increase transparency, thus enhancing e-waste management. Furthermore, the DPPs also align with the core element of *stretch the lifetime.* Because it makes product lifecycle transparent and traceable, they can help guarantee that components can be repaired, reused or recycled.

DPP usefulness in recycling is directly aligned with the CE principle of *cycle flows.* As stated before, this principle focuses on reusing materials and products at their EoL, creating a circular flow of resources. In this sense, DPPs can provide valuable information to stakeholders in the VC, namely recyclers, on how to disassemble appliances and recover valuable materials. However, it is essential to remember, as indicated before, that this is only true if attention is given not only to the upstream of the VC but also to the downstream. As it was highlighted by Interviewee 1, there is a need for a more automated process to allow for DPP scanning in bulk. This way, DPPs would become helpful for those who work at the end of the VC. Going deeper into the KE framework, the DPPs also connect to the core element of *use waste as a resource,* which means that DPPs can enhance recycling by providing the information for material recovery at their EoL. This assists with using waste as a resource, thus, encouraging a closed-loop system.

Regarding the potential benefits of DPPs in reuse and repair, the CE principle of *slow flows* encourages extending products' lifespan through repair, refurbishment and reuse. Thus, the DPPs can contribute to this by providing valuable information to users on how to repair products, where to bring them in case of professional repair and the necessary information to keep products in use for longer. This allows for optimisation of resource use as well as reduction of extraction rates. The DPPs also directly relate to the KEs of *stretch the lifetime* and *design for the future.* As stated before, the DPPs allow for the product lifespan extension by facilitating repair and reuse. This helps products stay in use for longer and, thus, stretch its lifetime. Beyond that, the DPPs also indirectly encourage manufacturers to design their products for repair, making them easier to disassemble and, therefore, design products for the future.

Moreover, when it comes to product lifecycle extension*,* two main enabling and core elements arise, namely *design for the future* and *incorporate digital technology*. Since DPPs provide lifecycle data on electronics, it also allows businesses to design their appliances with the EoL already in mind, allowing for easier repair and recycle. Beyond that, digital technologies, such as the DPPs, are a tool for optimising circularity, providing the foundation for all product information, managing and sharing data across the entire VC. According to Report C, “Actors along the value chain must be able to communicate efficiently – and thus automatically - via interfaces to be able to transmit relevant information without losses and in a resource-saving manner.”, which can be delivered by the DPPs. Additionally, the DPPs as a whole also significantly support the enabling element of *rethink the business model,* since they enable new manners to employ new products through for example, repair services etc. The DPPs significantly contribute to rethinking the traditional linear business model and focusing on circular business models.

Overall, the DPPs significantly support CE practices. DPPs directly support three out of the four CE principles, namely *cycle flows*, *narrow flows* and *slow flows*. Beyond that the DPPs are also strongly linked to the core and enabling key elements of CE. Therefore, DPPs definitely promote circular economy practices.

CONCLUSION

The overall goal of this research was to assess the role of DPPs in enhancing e-waste management and promoting CE practices in the consumer electronics sector. It explored the effectiveness of DPPs in managing e-waste, determining its benefits, limitations, and challenges, and evaluating how DPPs can help promote circular economy practices.

Linear economic practices heavily drive e-waste management in the consumer electronics sector. As indicated before, there is a need for a transition towards circular economy and circular business models. In order to tackle the growing amount of e-waste, CE principles should be applied to the sector. However, several technological, regulatory and economic barriers, such as few financial incentives, high upfront investments or fragmented e-waste management regulations, hinder the adoption of CE principles in this sector. Besides that, consumer behaviour and the 'always need to be on trend' behaviour encourage that.

Looking deeper into the EU, the WEEE Directive has a crucial role in assisting in managing e-waste. However, more is needed to improve circularity and other environmental aspects within the EU. Although recycling rates are higher compared to other continents, they are still not sufficient when considering the amount of electronics entering the market. The ESPR, which entered into force in July 2024, was an essential complement to EU regulations, offering the DPPs as a driver of compliance and innovation in product lifecycle management.

In this context, the thematic analysis of three reports and two expert interviews were conducted to understand better the DPPs' direct effects on e-waste management and the underlying challenges that could influence its adoption and performance. Additionally, this analysis allowed for a comprehensive overview of how the DPPs can promote CE practices.

The results show that DPPs indeed can improve e-waste management in the electronics sector. This is done by offering transparency across the entire value chain, improving traceability throughout the product lifecycle, and facilitating better material and component tracking. Beyond that, they are highly beneficial in reuse and repair by providing the data needed for such repairs. However, for the DPPs to be efficient, they should include reliable and up-to-date data on components and products.

Furthermore, the results show that the DPPs facilitate the repair, reuse, and recycling of products and materials, resulting in more resource-efficient practices. Moreover, the DPPs are closely aligned with three out of the four CE principles, namely *narrow, slow,* and *cycle flows*. Overall, they support transparency in product lifecycle data, motivating manufacturers to design and develop more circular and durable products.

However, even though DPPs are beneficial, there are some challenges to their implementation, including high costs—especially for SMEs—the dilemma between data transparency concerns involving data confidentiality and the difficulty of integrating DPPs across different systems and industries. All these must be overcome for a smooth implementation.

Therefore, to avoid any future troubles, it is essential that companies actively participate in helping shape DPP regulations. They should voice their concerns, clarify their doubts and provide any ideas that might help with the adoption of the DPPs. The DPPs can only be successful if the regulatory challenges and limitations are overcome.

There are some limitations to this research that should be acknowledged. Because this research adopts a qualitative method, namely semi-structured interviews and thematic analysis, the findings might not be generalizable. This means that one may not be able to apply the research results to broader contexts or sectors beyond consumer electronics. This is due to the in-depth characteristics of this research method.

It is also important to emphasize that the data came from a limited number of stakeholders, namely two interviewees and three reports, limiting the diversity of viewpoints regarding the DPPs. Consequently, this could impact the comprehensiveness of insights that arose from this research. Another limitation is related to the method of data analysis chosen, thematic analysis. Because a deductive approach to the data was chosen, it is possible that researcher bias was instituted when deciding on themes. Even though this approach helped offer some guidance to develop the research, it could also have restricted some themes from emerging in the first place.

Lastly, it is also important to note some limitations related to the amount of previous research on DPPs. Because this is a somewhat new subject, the literature is limited. Therefore, it is also crucial to address the challenges and limitations here uncovered in future research.

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Appendix

Annex A – Semi-structured interview guide

E-waste management recycler (Renewi)

- What are the current challenges your organization faces in managing e-waste?
- How could DPPs help overcome these challenges? (efficiency/effectiveness)
- What specific information provided by DPPs would be most beneficial for your operations in terms of enhancing e-waste management?
- In what ways do you think DPPs can support a circular economy?

DPP Developer (Eviden)

- What types of DPPs are you developing?
- What is the main goal when developing DPPs?
- How easily do you think DPPs can transfer to other products to achieve similar goals?
- What are the main challenges, in general, in developing DPP (for electronics)?
- What are the potential barriers to integrating DPPs in the electronics sector?
- What is the biggest challenge when it comes to DPP infrastructure for electronics?