Enhancing electronics materials recovery through effective design practices: review on recent applications

Laila El Warraqi, Paolo Rosa, Sergio Terzi

Department of Management, Economics and Industrial Engineering, Politecnico di Milano, via Lambruschini 4b, 20156 Milan, Italy (laila.elwarraqi@polimi.it, paolo1.rosa@polimi.it, sergio.terzi@polimi.it)

Abstract: Today's continuous increasing production in the electronics industry has brought several challenges concerning waste management, emphasizing the need for sustainable solutions that support materials recovery. This issue emerges once electronics reach their end-of-life (EoL), becoming necessary to dispose or recover them. However, before disposal it is appropriate to analyze the composing materials. Indeed, electronics materials encompass a wide range of elements – such as metals, semiconductors, plastics, glass – and their recovery allows the extraction of valuable resources such as precious metals and allows waste reduction and energy savings. However, in many cases such considerations are only made at the EoL of the electronics and thus sometimes the recovery process becomes challenging as during the design stage, therefore at the beginning-of-life (BoL) of the electronics, are neglected strategies that can facilitate the materials recovery and recycling at the EoL. This paper wants to analyze design practices, focusing especially on design for recycling and design for disassembly, to enhance electronics' materials recovery and recycling by providing a comprehensive review on recent applications considering publications of the last decade to assess the overall benefits of the latest implemented approaches.

Keywords: e-waste, design practices, disassembly, recycling, recovery

1.Introduction

Electronic waste is considered to be one of the fastest growing waste streams in the world (Cucchiella *et al.*, 2015) and this is also due to the increasing consumption of electronic devices and the short lifespan of these products; indeed, new technologies are rapidly replacing similar appliances leading to their disposal in prescribed landfills causing therefore adverse impacts to the environment (Kiddee, Naidu and Wong, 2013). It is required that such products, once they reach their end-of-life (EoL), go to proper disposal, recycling, and reuse strategies to prevent from waste generation. Indeed, as Europe moves towards Circular Economy (CE) and deals with problems related to the environment, this leads to the creation of several regulations and policies related to the environment (Mishra, Siwal and Thakur, 2024). The transition towards CE is crucial in the electronics sector, given the increase of waste that records. This will allow substituting the EoL notion with restoration and closed-loop product lifecycles, eliminating wastes and retaining the value embedded into products (Sassanelli *et al.*, 2019). Waste of electrical and electronic equipment (WEEE) includes all the components of such products, which have stopped working or suffered from function defects during their production (Silvas *et al.*, 2015). Improper WEEE management can cause hazardous fumes and chemicals, posing risks to both human health and environment (Awasthi *et al.*, 2018). These issues must be addressed through waste recycling and recovery practices; indeed, recycling of WEEE is an important subject for waste treatment and also for the recovery of valuable materials. However, a great amount of the global waste from electronics is not managed correctly (Ghisellini, Cialani and Ulgiati, 2016). Indeed, usually the waste issue is taken into account only once the product reaches its EoL. Usually, the challenge that a manufacturer faces relates to the identification of the optimal route for EoL products, to understand whether their components need to be reused, recycled, or will end up in a landfill (Iakovou *et al.*, 2009). The application of eco-design practices, such as design for disassembly, design for recovery and design for recycling at the beginning of products' lifecycle (BoL), can support choosing the optimal EoL route and reduce the environmental impact brought by such products. However, due to the complexity of application of such strategies, usually they are not implemented by manufacturers, neglecting therefore the importance of the integration of the different decisions taken at the different lifecycle stages. Indeed, usually electronic products contain valuable materials (e.g., copper, silver, gold, indium), therefore, designing products implementing recovery, recycling or disassembly practices can ensure that these materials can be efficiently recovered and reused. As these problems are often neglected, this paper aims at providing a study on strategies for design for recycling, for recovery and for disassembly of electronic products to fill these gaps. To this end, the rest of the paper is structured as follows. After presenting a brief introduction to the issue of e-waste management, Section 2 provides a brief analysis on the approaches that address electronics waste, also including an overview on the design practices. Section 3 provides the literature review, presenting both the methodology and the results. Section 4 includes the discussion of the analysis. Finally, Section 5 provides the conclusions, together with an outlook on future works of investigation.

2.Electronics waste issue

Electronics products face great obsolescence issues, and often this is linked to a business strategy that encourages consumption and coupled with the reduction of the useful life of products and their components, it encourages continuous products replacement. Indeed, due to this fast obsolescence, products such as computers, desktops and cell phones correspond to the largest number of residues (Nunes *et al.*, 2021). These products indeed compose a great part of electronics, and their components are usually produced from heavy metals such as copper, arsenic, mercury, lead, cadmium which are considered very toxic (Nunes *et al.*, 2021). Different studies are performed concerning the impact of e-waste, such as the product-service-system (PSS) one which aims at producing products meeting users' requirements while also reducing the environmental impacts. To integrate the PSS strategy, it is relevant that products are planned in all aspects from the beginning to the end of life of their lifecycle (Beuren, Gomes Ferreira and Cauchick Miguel, 2013). Having in mind the requirements of a PSS product, it is then relevant to classify the different elements included in the WEEE and treat them in an optimal way. Indeed, the results of a product that attains to PSS requirements include the extension of the useful life of raw materials used in manufacturing and the design of modular parts that facilitate the EoL management, including the disassembly of products to allow recovery and/or recycling processes. As stated by Nunes *et al.* (2021), once the electronic product reaches its EoL, the WEEE incurs different steps that goes from the removal of raw materials to their reuse or recycling or disposal in landfills. In particular, at the end of their useful life, electronics products can be deposited in landfills, disassembled or redistributed to industries that give them a second useful life (therefore, in this sense, products are reused or recycled).

Already at the design phase of these products – therefore at the BoL stage – it should be clear how they will be managed once they reach the EoL. Manufacturers need to understand how to link the design phase, with the use phase and the EoL stage. In particular the BoL phase plays a relevant role, since it is the phase where it is required to choose the right materials and understand how to compose products effectively through the right design practices. However, to the best of the authors knowledge, current literature does not provide a study on such practices and on their benefits in the electronics sector.

2.1 Design practices

Research in the manufacturing field allowed several companies to develop and implement guidelines for product use during the design stage. Kuo, Huang and Zhang (2001) provided an analysis on the design practices implemented by manufacturers across the years. Early studies contributed on the design of individual parts for "producibility", then, as reported in (Kuo, Huang and Zhang, 2001), Boothroyd, Poli & March in 1978 conducted a research on *design for assembly* (DfA) to consider the assembly constraints in terms of methods and costs during the design phase. In 1997, Stoll expanded the studies on DfA to *design for manufacture* (DfM), with the aim of considering all the design goals and constraints for the products that will be manufactured. These are the first practices implemented at the design stage in order to optimize the subsequent stages of the lifecycle; indeed, the implementation of DfA and DfM led to benefits in terms of reduction of costs, quality improvement and reduction of time to market. However, both strategies did not consider the environmental concerns, and therefore researchers and practitioners started to understand the need to shift to other solutions which also include environmental challenges. Remanufacturing is one alternative that allows bringing products back to their useful life while maintaining the geometric shape of the parts. Another alternative that considers environmental issues is recycling and to retrieve essential elements within a product, disassembly is a needed step (Soh, Ong and Nee, 2015). Indeed, disassembly is required for many strategies including recycling, maintenance and remanufacturing therefore, research efforts have been made in order to improve this process. The design for disassembly (DfD) is one of the studies which discusses and proposes aspects such as disassembly sequence generation (Soh, Ong and Nee, 2015). At the basis of this approach there is the need of considering both design and manufacturing as linked to each other. Products that are designed for disassembly and remanufacturing can deliver higher savings. On the other hand, recycling became an issue considered in many countries and it has been recognised that the disassembly of used products is a further step necessary to make recycling feasible. However, challenges related to the disassembly of products are connected to manufacturers that often do not design products for an ease disassembly. This issue makes also challenging to understand how to plan the disassembly once the product reaches its EoL. Indeed, across the lifecycle, products may incur to modifications (e.g., repair of some parts), and therefore they could differ from how they have been designed at the BoL, making the disassembly step more challenging. As stated by Kuo, Huang and Zhang (2001), another critical problem is the sequence of disassembly and as determined by Dewhurst (1991) three issues are associated with disassembly which can be stated as: i) freeing the part of all attachments, ii) finding the succeeding part in the disassembly sequence, iii) disassembly of the succeeding parts. Designers and manufacturers should consider the specificality of the considered products in order to evaluate their disassemblability and recyclability.

Linked to the recycling issue, studies are being performed at the BoL in order to improve the EoL recycling of products through the so-called design for recycling (DfR). While the DfD specifically focuses on optimizing the disassembly process in order to perform strategies such as remanufacturing, maintenance or recycling; the DfR has the aim of providing guidelines in order to design a product at the BoL based on facilitating the recycling process and maximizing the outcome from it (Leal *et al.*, 2020). Indeed, a product designed considering DfR should be also easy to disassemble, and the different product parts should be of the same material in order to prevent from contamination during recycling at the EoL (Hassiotis, 2015). Both DfD and DfR are linked to each other as they both support recovery strategies and applied to electronics can reduce the waste generation.

3.Literature Review

3.1 Methodology

Given that the objective of this paper is to provide an analysis on how design practices – in particular DfD and DfR – can be used to support the waste management in electronics, the research has been guided by the following research question (RQ): “How are design practices currently used in order to enhance materials recovery from electronics?”.

To respond this RQ, a systematic literature review has been conducted using Scopus and Web of Science as research databases considering the following keywords and logical connectors:

“electronic” AND (“design for recycling” OR “design for disassembly” OR “design for recovery”).*

110 papers resulted from Scopus and 75 from Web of Science and, after eliminating duplicates, a total of 134 documents have been considered, however several ones were out of the scope of the analysis and therefore have been excluded. In particular, the inclusion criteria can be summarized as follows.

- The literature review has been limited to papers published during the last decade, in order to capture the latest advancements, methodologies and perspectives on this research topic.
- The analysis included papers focusing on DfR and DfD, but also on papers applying generic design strategies that optimize recycling and/or disassembly procedures for materials recovery.

In particular, among the 134 papers, 51 were published between 2013 and 2024. Among the 51 papers, 25 have been excluded as they did not provide an analysis on the usage of design practices in electronics, instead they were focused on circular economy principles in the electronics sector without linking them to design practices or were focused on other practices for e-waste management at the EoL.

As result, 26 papers have been included in the final analysis. These papers are presented in Table 1; each column of the table will be further analysed in the next sections.

3.2 Results of the analysis

Table 1 reports the analysed papers clustered by the implemented design practices which have been divided into: a) DfR: in case papers refer specifically to recycling strategies applied at the design stage of the electronic element, b) Generic design practices that support recycling and/or disassembly at the EoL stage of electronics, c) DfD: in case papers refer specifically to disassembly strategies applied at the design phase.

Table 1: Literature review – Papers analysis

Reference	Electronic element	Design practice	Impact on lifecycle phases
(Paz *et al.*, 2024)	Refrigerator	DfR	BoL, EoL: recovering valuable materials such as aluminum, copper, and iron from discarded appliances. Contribution to a more sustainable approach to manage electronic waste.
(Sudheshwar *et al.*, 2023)	Printed electronics	DfR	BoL, EoL: facilitate the recycling phase of printed electronics once products reach the last stage of their lifecycle
(Ferro and Bonollo, 2019)	Generic: Critical raw materials recycling	DfR	BoL, EoL: integrate design for recycling practices into the lifecycle phases to facilitate recycling at the EoL
(Köhler, 2013)	E-textile	DfR	BoL, MoL, EoL: the integration of DfR principles in the design process can influence how e-textiles are used, maintained, and recycled or disposed of at the end of their life cycle.
(Reuter and van Schaik, 2015)	LED lamp	DfR	BoL: impact on the design phase of LED lamps. EoL: optimize the recyclability of LED lamps.
(Narimatsu *et al.*, 2013)	Electrical and electronic product - LCD TV	Generic: evaluation of different design practices to assess the ones that optimize the recyclability rate	BoL, EoL: increase of the recyclability rate while keeping the disassembly time of the original design
(Doyle, Cavero and Modreanu, 2023)	Generic: electrical devices	Generic: application of the principles of green engineering at the design phase	BoL, MoL, EoL: minimize waste generation, and promote efficiency in mass, energy, space, and time utilization. EoL: facilitate easier recycling and reuse of components by designing products with targeted durability.
(Fenwick *et al.*, 2023)	Generic: Electrical and electronic equipment	Generic: eco-design practices to improve the recycling phase	BoL, MoL, EoL: eco-design practices to minimize the environmental impact of products throughout their lifecycle. EoL: improve the recyclability of plastics from e-waste.
(Berwald *et al.*, 2021)	Generic: Electrical and electronic equipment	Generic: design for circularity to support recycling strategies	BoL, MoL: usage of recyclable materials. The design for circularity guidelines can lead to the use of recyclable materials and material combinations that facilitate recycling EoL: products are designed to be more easily disassembled and recycled.
(Movilla, 2015)	Generic: Electrical and electronic equipment	Generic: design for recovery	BoL: encourage manufacturers to promote the design of products in order to perform a more efficient recovery. EoL: products efficient recovery at their EoL phase.
(Huang, 2013)	Generic: Electrical and electronic product	Generic: design principles that improve the recyclability	BoL: influence the initial design choices to enhance recyclability and ease of disposal. EoL: optimize collection, transportation, disassembly, and material recovery processes that occur at the end of the product lifecycle.

(Romano *et al.*, 2023)	Power electronic converters	Generic: design for circularity or design for modularity to enable disassembly, repair/maintenance, reuse, upgrade, recycling	BoL: contribute to a modular design using modular parts. MoL: improve maintenance of power electronic converters thanks to modularity aspects. EoL: modularity enhance disassemblability and recyclability.
(Arroyos *et al.*, 2022)	Mouse	Generic: design principles to improve sustainability and recyclability	BoL, MoL, EoL: consider sustainable practices throughout the entire lifecycle phases. EoL: improve the end-of-life disposal procedure for the biodegradable circuit board
(Matarin, Gasol and Peiró, 2022)	Household electronics	Generic: design for repairability which improves the disassembly phase	BoL EoL: allow easier products disassembly, diagnosis, and repair, which can extend the product's lifespan and reduce the generation of electronic waste.
(Parajuly *et al.*, 2016)	Robotic vacuum cleaner	Generic: design for EoL to improve product recycling efficiency	BOL: need for product designers to consider factors such as material composition, ease of disassembly, and material compatibility to facilitate recycling processes. EOL: EoL phase of RVCs and how the design features of the product impact material recovery during recycling processes.
(Hickey *et al.*, 2014)	Laptop computer	Generic: design for recycling, repair, refurbishment and reuse	BoL, MoL, EoL: designing products with the intention of facilitating reuse and recycling. Simplification of disassembly and component replacement, allowing easier repair and upgradability of laptops.
(Khor, Ramayah and Fouladgaran, 2020)	Generic: Electrical and electronic equipment	DfD	BoL, EoL: facilitate the recovery of valuable subassemblies, component parts, and materials during the end-of-use phase, which is crucial for effective e-waste management
(Peeters *et al.*, 2017)	Generic: Electrical and electronic equipment	DfD	BoL, EoL: ease and efficiency of disassembling the product for recycling, refurbishing, remanufacturing, or disposal.
(Peeters *et al.*, 2015)	Generic: Consumer electronics	DfD	BoL, EoL: increase the recovery of precious metals, critical and rare earth elements, and plastics through systematic disassembly
(Liao *et al.*, 2023)	Computer desktop	DfD	BoL, EoL: simplify the separation of components, making it easier to recover valuable materials and reduce electronic waste
(Saunders, 2022)	E-textile	DfD	BoL, EoL: considering how products are designed and manufactured, design for disassembly will facilitate easier disassembly and recycling at the EoL.
(Talens Peiró, Ardente and Mathieux, 2017)	Battery packs of electronic devices	DfD	BoL, EoL: facilitate the disassembly of PC-tablets and subnotebooks
(Huang, Liang and Yi, 2017)	Mobile phone	DfD	BoL, MoL: DfD can lead to more efficient manufacturing processes. Accessible components can be quickly replaced or repaired, extending the product's lifespan and reducing downtime. EoL: easy disassembly facilitates recycling and proper disposal of components, contributing to a more sustainable approach to product lifecycle management.
(Long *et al.*, 2016)	Mobile phone	DfD	BoL, EoL : enhance EoL treatment process facilitating the identification and recovery of valuable materials and components from discarded electronic products.
(Hassan *et al.*, 2016)	Laptop computer	DfD	BoL, MoL: implementing DfD approach, the manufacturing process can be optimized for easier disassembly, reuse, remanufacture, and recycling of laptop components. EoL: enable reuse, remanufacture, and recycling of laptop components at the end of their life cycle.
(Alonso Movilla *et al.*, 2016)	Flat panel display	DfD	BoL, EoL: facilitates the development of ecodesign strategies that can improve product disassemblability. By analyzing dismantling practices and identifying design improvements, the method focuses on enhancing the disassembly process.

The table reports the impacts that the design practice has on the lifecycle phases of the considered electronic element, when reported in the text. Indeed, by implementing the design practices, the BoL and EoL phases will certainly be impacted, while in some cases the impact on the MoL phase is not explicitly mentioned. In the following paragraphs, the papers are analysed based on the used design practice to emphasize the overall benefits.

3.2.1 Design for Recycling (DfR)

Paz *et al.* (2024) conducted a study on recycling initiative focusing on the recycling of refrigerators. The implementation of DfR supported primarily the manual dismantling to extract valuable materials, such as aluminium, copper and iron form the discarded appliances, at their EoL. The resulting ferrous, non-ferrous and polymer product fractions were analysed and categorized, providing valuable insights into the quality of interim products in the recycling process. (Sudheshwar *et al.*, 2023) proposed a study that compares conventional printed circuit boards (PCBs) with paper-based printed electronics that offer flexible, bio-based, and biodegradable substrates with circuit design printed using silver-based inks. The study includes a comparative lifecycle assessment between the two options and assesses the relevance of e-waste recycling to paper-based printed electronics sustainability. It has been assessed that the application of DfR at the BoL phase of this material allow the recycling of silver at the EoL thus allowing reaching a consistent sustainability advantage over PCBs. Ferro and Bonollo (2019) proposed the DfR strategy to support the EoL recycling process of electronic products and extract critical raw materials (CRMs) and reduce their supply risks. This allow responding the challenge identified by the European Union on the number of raw materials strategic for the European economy but suffer from high supply risk. Köhler (2013) discussed eco-design strategies including DfR for electronic textiles reviewing existing guidelines that address environmental impacts, energy and resource saving. The application of eco-design practices and DfR supports waste minimization, allows sustainable practices throughout the lifecycle of e-textiles and allows labelling the e-textiles to facilitate their recycling. Reuter and van Schaik (2015) emphasized the importance of a product-centric simulation approach in DfR for LED lamp recycling. In their study, the authors highlighted the significance of using rigorous modelling techniques and simulation tools to analyse the complexities of recycling processes, quantify recycling rates, identify opportunities and limitations of recycling, and optimize product design and recycling options.

3.2.2 Design practices for materials recovery

As already stated under the Methodology Section, the analysis has been extended also to papers that include generic design strategies that optimize recycling and/or disassembly procedures and recovery of materials, in order to obtain an overall assessment. Narimatsu *et al.* (2013) proposed a design support method to increase the recyclability of electrical and electronic products. The method estimates the recyclability rate and the disassembly time of a product based on its material composition and EoL scenario. To this end, the paper analyses various design strategies and evaluates the ones that optimize the recyclability rate while maintaining the disassembly time of the original design of an LCD TV. Doyle, Cavero and Modreanu (2023) studied the application of the 12 Principles of Green Engineering in the early technology development phase. Considering the case of electronics, the paper specifically evaluated the technological areas of design for disassembly, materials for substitution, fabrication efficiency and manufacturing processes that enable the use of recycled materials. This allowed to identify hazardous raw materials and recommend their substitution, thus improving the entire lifecycle of the product and supporting the increase of their lifespan and the potential of their reuse. Fenwick *et al.* (2023) investigated the effectiveness of eco-design measures on plastics recycling in the context of WEEE within the European Union. This study impacts the overall lifecycle of EEE as it reduces their environmental impact from design to disposal. Berwald *et al.* (2021) provided a comprehensive design for circularity guidelines that harmonize design strategies for/from recycling of EEE to facilitate the closing of material loops within a circular economy. Movilla (2015) provided a study on *design for recovery* considering the diversity of the pre-treatment practices. Therefore, the paper presents a qualitative analysis which allowed to create a model containing the parameters that influence the functioning of French WEEE pre-treatment centers. The statistical analysis has been used to define groupings of pre-treatment operators to support the recovery phase at the EoL. Huang (2013) presented a mathematical programming model as a tool to identify the best design plan for the optimization of waste from electrical and electronic products reverse logistics costs. This strategy, at the EoL allows the optimization of collection, transportation, disassembly, and material recovery processes that occur at the end of the product lifecycle. It emphasizes the importance of efficient disassembly and material recovery to maximize the reuse and recycling. Romano *et al.* (2023) proposed a study on design for circularity and design for modularity to enable the disassembly, repair, maintenance, reuse, upgrade and recycling of power electronic converters. Arroyos *et al.* (2022) demonstrated how design techniques, such as using biodegradable materials, can lead to a circular production cycle for electronics. The authors developed a functional computer mouse prototype using biodegradable PCBs which allowed assessing the increased potential of the electronic element to be recycled and reused at the EoL. Matarin, Gasol and Peiró (2022) conducted a study on household electronics by reviewing methods for assessing their repair and repairability, identifying opportunities for improvement. The results showed that regular maintenance and material selection are potential key aspects to maximize the durability of some of their priority parts. Parajuly *et al.* (2016) proposed a methodological approach to assess the end-of-life (EoL) performance of electronic products, using robotic vacuum cleaners (RVCs) as case study. By analyzing the material flow and recovery processes of RVCs, the paper highlights the importance of integrating product design with appropriate EoL processing to improve resource recovery efficiency. Hickey *et al.* (2014) presented a study of design for recycling, repair, refurbishment and reuse considering a laptop to facilitate the integration of by-product materials and components into the manufacturing process. Indeed, the study emphasized the role of industrial networking in transforming waste into valuable resources and the importance of eco-design strategies in achieving zero waste goals. This strategy impacts the entire lifecycle of laptops as it can extend their lifespan, reducing the frequency of new manufacturing processes and associated energy consumption and carbon emissions.

3.2.3 Design for Disassembly (DfD)

Khor, Ramayah and Fouladgaran (2020) focused on reverse logistics strategies and assessed that by incorporating DfD principles into eco-design practices, companies can enhance their reverse logistics processes and achieve environmental and monetary benefits. The proposed strategy facilitates the recovery of valuable subassemblies, component parts, and materials during the end-of-use phase. Peeters *et al.* (2017) presented a methodology that enables Original Equipment Manufacturers (OEMs) and governments to accurately quantify the economic and environmental benefits of implementing design for de-manufacturing, specifically focusing on DfD. The methodology aimed at also evaluating the economic viability of incorporating active fasteners in electronic products and to assess the environmental impacts of such design strategies and support efficiency of disassembling the product for recycling, refurbishing, remanufacturing or disposal. Peeters *et al.* (2015) presented a study on the development and evaluation of elastomer-based fasteners as a solution to facilitate rapid disassembly for consumer products. The focus was on improving the efficiency of end-of-life treatment processes by reducing disassembly time through innovative fastener design, specifically using elastomer materials. Liao *et al.* (2023) had the aim of finding the optimal disassembly sequence allocating disassembly tasks between humans and robots. The study considered a computer desktop and aimed at optimizing the disassembly process by considering factors such as cost, disassemblability and safety in a human-robot collaboration setting. Saunders (2022) proposed a study that assessed how incorporating DfD principles influences the design process, materials used, and overall waste management strategies in the e-textiles industry. The results of the study provided suggestions on the development of a sustainable waste framework and underpin policy development for e-textiles waste. Talens Peiró, Ardente and Mathieux (2017) presented a method for analyzing the removal of battery packs in newer portable computer models as an example on how the DfD of batteries can affect the life span and potential reuse of such computers. Huang, Liang and Yi (2017) provided disassembly guidelines and recyclable component classification to instruct how to disassemble components considering the case of mobile phones. Additionally, based on a cloud computing architecture, the authors demonstrated how designers can exchange and store their design information and knowledge for new sustainable product development. Long *et al.* (2016) assessed the disassembly of mobile phones where component materials, weight, possibility of re-attachment and damage of disassembly were identified and noted down for every removed component. This disassembly gave insight in how the WEEE management in the EU could be adapted to improve the amount of component recovery. Hassan *et al.* (2016) investigated existing laptop computers towards sustainable development using DfD methodologies. The study aimed to address problems related to repairing and upgrading laptop components, reduce environmental waste, and achieve sustainable development goals. Alonso Movilla *et al.* (2016) analyzed disassembly activities focusing on the recycling of Flat-Panel Displays through manual dismantling operations. The aim was to provide solid evidence to support the development of quantified indicators and specific design guidelines tailored to the needs of treatment operators in the WEEE recycling industry.

3.2.4 Overall benefits

The analysed papers that consider the analysed design practices at the initial phase of the lifecycle allow the assessment of the main benefits resulting from the application of the different approaches. Indeed, the benefits that could be obtained are common to most of the applications, since as already pointed in Section 2.1, DfR and DfD - and the design strategies that support the EoL e-waste management - allow considering aspects that improve the environmental sustainability. The main benefits can be grouped into: i) environmental impacts reduction – as the recycling of materials supports the reduction of raw materials extraction (e.g., Ferro and Bonollo (2019) explicitly stated that DfR reduces the risks of CRMs supply); ii) resource conservation - using recycled materials contribute to resource conservation and sustainable material use (e.g., Köhler (2013) suggests that using recycled fibres, minimizing the consumption of scarce metals and primary resources in the production of electronic textiles, contributes to resource conservation); iii) promote circular economy by reusing recycled materials, therefore closing the loop (e.g., from Romano *et al.* (2023) study it is possible to assess that modularity enables easier disassembly, repair, maintenance, reuse, upgrade, and recycling of printed electronics, contributing to a more circular product design); iv) compliance with regulations and policies – there is a lack of consideration of regulations and legislation factors. However, as highlighted by (Köhler, 2013), in the case of e-textile, adhering to eco-design principles, including those related to recycling, can help e-textile manufacturers align with existing and future regulations. Saunders (2022) study on the incorporation of DfD principles into waste policy design for e-textilesto fill the gap in e-textiles waste legislation; v) costs efficiency – e.g., in Huang (2013) the mathematical programming model, besides identifying the best design plan allowed optimizing reverse logistic by considering factors such as transportation, disassembly, material recovery, and waste disposal costs allowing manufacturers to reduce overall expenses, in Alonso Movilla *et al.* (2016) study it is possible to assess that products designed for easier disassembly require less time and effort to break down into individual components, lowering operational expenses; vi) improve product longevity, specifically in the case of DfD, since easier disassembly can lead to products repairability, therefore increasing their lifecycle.

4.Discussion

The *Overall benefits* Section allowed evaluating the effectiveness of the discussed design practices in promoting sustainability and CE within the electronic sector. Some of the analysed cases emphasize the importance of collaborations among stakeholders to allow effective management of the entire electronic lifecycle, from raw materials extraction, to design, to manufacturing, to EoL practices (e.g., recycling). Indeed, at the basis of the implementation of effective design practices lies the challenge of applying a lifecycle thinking approach, since electronics developers not only need to focus on the design stage, but also on the consequential stages, considering collaborations with all the specific actors involved at each step of the lifecycle. Additional stakeholders that need to be considered are policymakers; indeed, few papers considered the relevance of policies and regulations in guiding companies to manage e-wastes. Legislations play a crucial role and need to be considered by electronics developers in order to not infringe WEEE directives. Another relevant role is played by technologies in supporting the overall lifecycle of electronics. For instance, the usage of technologies can support both the design stage and the EoL management. However, developers, in most cases, still face difficulties on exploiting advanced technologies and this is due to both the lack of knowledge on these tools’ assistance benefits, as well as the lack of expertise on their usage.

5.Conclusions

This paper proposed an analysis of design practices that support the recovery of electronics through recycling and disassembly. The analysis focused on papers published in the last decade in order to capture the latest advancements, methodologies and perspectives on this research topic and allowed to assess the benefits of implementation of the considered design practices, and to assess some challenges for an effective e-waste management. In particular, by applying design practices, common benefits could be obtained by electronics manufacturers, which could be grouped as: i) environmental impact reduction, ii) resource conservation, iii) promotion of circular economy, iv) compliance with regulations and policies, v) cost efficiency, vi) improvement of products longevity. Furthermore, in order to obtain these benefits, at the basis of the implementation of effective design practices lies the challenge of applying a lifecycle thinking approach.

Despite the relevant results of the provided analysis, this paper has some limitations that the authors will address in future works; the paper does not provide an analysis on existing regulations in order to link them to the current applications of e-waste management and it does not include an analysis of digital technologies, and how they could be used in order to support decisions for e-waste management. Additionally, this analysis will require also to be extended to other design practices.

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