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Equipping Designers with Sustainable Practices: Solutions for Making Small Electronic Devices Greener

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Declaration of originality

I, Miguel E. Zambrano Campitelli, hereby declare that the work presented in this dissertation, titled " Equipping Designers with Sustainable Practices: Solutions for Making Small Electronic Devices Greener," is entirely my own original work. I affirm that it has not been fully or partially submitted previously in any other Italian or foreign university for assessment purposes.

I further confirm that the content of this dissertation is the result of my own intellectual endeavors, and I have appropriately cited all sources used. This work does not infringe upon the intellectual property rights of any third party, and its contents do not constitute plagiarism.

I understand the consequences of submitting work that is not my own and affirm the honesty and integrity of this academic contribution.

Miguel E. Zambrano Campitelli

Abstract

Small Electronic Devices (SEDs) represent a worrying fraction of the unsustainable electronic waste problem, especially nowadays with their increasing demand due to digitalization. Given their strategic role in the life cycle of a product, designers require sustainability know-how to make a positive impact on this issue while remaining responsive to market demands. This study addresses the critical need to identify practical solutions to equip designers. It identifies two distinct approaches to addressing sustainability in SEDs. The first approach focuses on components with superior eco-properties through innovative materials. The second approach centers on design guidelines to connect designers with end-of-life (EoL). Thus, this study conducts a supplier exploration in line with the first approach and a compilation of design guidelines contrasted with repairers and recyclers' interviews. The results present an overview of the components with superior eco-properties found during the supplier exploration, as well as an analysis of the relevance of the design guidelines to tackle the challenges for EoL handlers with SEDs, such as safe battery removal and time-consuming disassembly. The findings are then framed with the definition of sustainability and the field of circularity to illustrate their significance. The research finds that to overcome their limitations, it is necessary to utilize both approaches in conjunction with each other. On one side, there is a lack of ready-to-use options and design flexibility resulting from the first approach. On the other hand, design guidelines may challenge design priorities, such as aesthetics or producer liabilities. Notwithstanding, while sustainable solutions for greener SEDs may seem limited, this research resolves that implementing suggestions derived from this exploration would result in avoided impacts on the planet, serving as valuable resources for designers striving to make their creations more sustainable.

Preface

Ever since I started this master's and this journey into the realm of circularity, the wicked nature of sustainability has created contradictory thoughts. A disappointing one when delving into the complexity and intersectionality of the topic and the realization that many critical facts are unknown by others outside of the *sustainability bubble*, plus that these facts are tremendously challenging to tackle. In contrast, jumping into this field brings a feeling of fulfillment when realizing that contributing to this matter by popping the bubble and helping to spread knowledge on sustainability matters and that working to enable circularity is a promising approach for this complex issue. I believe this work, beyond its practical and academic value, is a representation of this optimistic side, where circularity is a worthwhile approach to be spread.

I thank this academic journey for introducing me and preparing me for what I expect will be a meaningful career path. Thus, I thank the people behind the master's degree in circular economy from UNIPD for creating an interdisciplinary and relevant course. Professors, tutors, peers, and friends for accompanying me. The company that hosted me for allowing me to explore the application of circular principles in a real case study, and all the company members who helped me during the internship. The people who agreed to offer valuable insights in the interviews for this thesis with the only purpose of helping and contributing to this topic.

Last but not least, my family for backing me to start this new chapter and always being present in my achievements despite the distance, and special thanks to an amazing person who not only gave me the best feedback during my thesis and studies but also accompanied me in this thrilling chapter of my life.

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Chapter 1. Introduction

The alarming annual growth rate of electronic waste (E-Waste), nearly 2 Mt globally (Forti et al., 2020), has earned it the title of *the world's fastest-growing solid waste stream* (Cesaro et al., 2018; Parajuly et al., 2019). Remarkably, small electronic devices (SEDs) constitute the largest portion of E-Waste[1], a concerning trend attributed to their short life spans and easy disposal compared to larger electrical and electronic equipment (EEE) (Dimitrakakis et al., 2009; Forti et al., 2020; Parajuly et al., 2019). The increasing need for SEDs further exacerbates the issue. While the demand for these products has long been linked to their convenience in simplifying everyday tasks, nowadays, it is boosted due to digitalization (Parajuly et al., 2019). For example, SEDs are now part of vital sectors such as health care, with wearable devices performing remote monitoring (Iqbal et al., 2021), a trend that underscores the fact that society now relies on SEDs more than ever.

The complex material composition of EEEs comprising plastics, base and precious metals, and critical raw materials (Cenci et al., 2022; Cesaro et al., 2018) raises concerns about mining, resource depletion, and greenhouse gas and hazardous pollutants emissions from extraction and refinement processes (Forti et al., 2020). Simultaneously, the inadequate end-of-life (EoL) management of E-waste, with only 17.4 % being properly collected and recycled in 2019 (Forti et al., 2020) poses questions about the loss of valuable resources and the dispersion of toxic elements like heavy metals and brominated flame retardants, which can harm ecosystems and human health (Ahirwar & Tripathi, 2021).

Considering these problematic facts, ideas such as "Green Electronics," aiming at mitigating the negative impacts of SEDs, are gaining momentum. This concept strives to introduce alternatives with a "net positive environmental impact when compared to existing electronics" (Cenci et al., 2022, p. 26). To this end, the literature has discussed initiatives such as the selection of materials with *superior eco-properties*, that is, with less harmful materials or features like biodegradability (Cenci et al., 2022). Another initiative is the design for X frameworks, where X stands for sustainability, recycling,

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[1] Considering the EU classification, small equipment is the largest fraction (17.4 Mt). Other SEDs may be included in different categories of the EU classification, like small IT (4.7 Mt). The total amount of e-waste in 2019 was 53.6 Mt (Forti et al., 2020).

or EoL, aiming to offer guidelines to connect designers with the EoL of their products (Berwald et al., 2021).

Addressing the issue at the design stage is strategic, as “80 % of a product's environmental impact is influenced by decisions made at the design stage” (Ellen MacArthur Foundation, 2022). Historically, traditional design and manufacturing prioritized easy assembly and productivity, reflecting the predominant economic system and drawing criticism for decades (Papanek, 1973; Shahhoseini et al., 2023; Tischner & Hora, 2019). This approach has often overlooked the strategic role of designers within the lifecycle of SEDs, where pivotal decisions are made concerning material selection, repairability, and even the influence on the EoL (Ellen MacArthur Foundation, 2022). To leverage this strategic position effectively, designers must possess a deep understanding of sustainability principles (Tischner & Hora, 2019).

This study stems from an internship experience with a SED manufacturer, portraying the growing importance for designers and manufacturers to integrate sustainable practices into their processes while operating within the constraints of the prevailing economic system, which favors mature and readily available solutions.

The primary objective of this research is to compile practical solutions to render SEDs more sustainable, providing valuable recommendations for designers. More significantly, this qualitative examination strives to delve into the sustainable rationale behind these solutions. Doing so lays the groundwork for other researchers to conduct quantitative assessments of the positive impact of the results and for designers to comprehend the effect of their decisions throughout the product's lifecycle, with a specific focus on the EoL phase.

To this end, this work focuses on two approaches. Firstly, a search on suppliers offering components with “superior eco-properties,” like printed circuit boards assemblies (PCBAs) and batteries, for a small, wearable, and remote monitoring medical device. The relevance of this approach is that many of the advances in materials with superior eco-properties are occurring in research settings, and original equipment manufacturers (OEMs) need ready-to-use solutions to build their products. While the focus on a specific SED for this search could be limited, it still provides a substantial overview of the state of the art for commercial electronic components in the field of sustainability.

Secondly, this work explores the design for X frameworks, gathering a diverse set of guidelines that could be helpful for designers to understand what the most crucial decisions in terms of sustainability are when designing a device. These guidelines focus on facilitating the EoL of the product, as this is one of the most complicated phases for EEE; therefore, an electronic repairer and two recyclers are interviewed to elaborate on the selected design guidelines and understand the challenges and influence that they have for each EoL handler. While the number of interviews is limited, the selection of the participants covered a significant set of expertise; moreover, information available in the literature complements their insights.

This work begins with a literature review, exploring the definitions of EEE, E-waste, and SEDs. It delves into their typical materials and EoL routes. The study then explores green electronics, examining the intersection of electronics and sustainability. This analysis defines common paths for green electronics, focusing on materials with superior eco-properties and the Design for X framework. Subsequently, the methodology involves systematic research on suppliers offering components with superior eco-properties and gathering information from their official websites and meetings. The compilation of the design guidelines involves the contrast of two main sources and the findings from the interviews. The results present supplier alternatives, discussing their characteristics, limitations, and opportunities, drawing on empirical insights from the internship experience. Design guidelines are thoroughly examined, refined, and compared with insights from interviews, leading to a discussion on their relevance in various EoL scenarios. Finally, the exploration wraps up with a discussion on factors designers should consider when creating green electronics, emphasizing EoL understanding and sustainability concepts. Lastly, the conclusion elaborates on the key findings, their relevance to the topic, and perspectives for future research on this subject.

Chapter 2. Literature review

2.1. Electrical and electronic equipment (EEE)

EEE is “any household or business item with circuitry or electrical components with power or battery supply” (stEP Initiative, 2014). The European Union’s waste electrical and electronic equipment (WEEE) directive 2012/19/EU possesses a similar definition that reads “[…] equipment which is dependent on electric currents or electromagnetic fields in order to work properly and equipment for the generation, transfer, and measurement of such currents and fields […].” (Directive (EU) 2012/19, 2012, p.3). Except for some cases, like filament bulbs and large-scale fixed installations, all EEE defined under the former definition also enter the scope of the EU definition (stEP Initiative, 2014).

EEE can be found in any household or business in the form of basic kitchen appliances, toys, gadgets, wearable devices, mobile phones, laptops, etc. Additionally, their presence is increasing in several sectors such as transport, health, security, and even textiles as a consequence of the expansion of the field of the Internet of Things related in turn to the concepts of digitalization (Forti et al., 2020).

2.2. EEE classification

A thorough categorization referred to as UNU-KEYs divides EEE into 54 different product categories for statistical purposes according to similar function, comparable materials, composition, average weight, and similar EoL scenarios. (Forti et al., 2018). A more condensed categorization is provided by the European Union (Directive 2012/19/EU, 2018; EWRN, 2019):

1. Temperature exchange equipment is EEE with internal circuits where substances other than water are used for the purpose of cooling, heating, and/or dehumidifying. It includes refrigerators, freezers, air conditioners, and heat pumps.
2. Screens, monitors, and equipment containing screens are EEEs whose intended usage focus is displaying images or information on a screen having a surface greater than 100 cm^2, for example, televisions, monitors, laptops, notebooks, and tablets.

3. Lamps are replaceable electrical devices that produce light from electricity; amongst that, they can also have other functions fluorescent lamps, high-intensity discharge lamps, and LED lamps.

4. Large equipment considers EEE not allocated in categories 1, 2, or 3 with any external dimension more than 50 cm. It includes washing machines, clothes dryers, dishwashing machines, electric stoves, large printing machines, and photovoltaic panels.

5. Small equipment considered EEE not allocated in categories 1, 2, 3, 4 or 6 with no external dimension more than 50 cm such as vacuum cleaners, microwaves, ventilation equipment, toasters, electric kettles, electric shavers, scales, calculators, radio sets, video cameras, electrical and electronic toys, small electrical and electronic tools, small medical devices, small monitoring, and control instruments.

6. Small IT and telecommunication equipment (no external dimension more than 50 cm) is EEE designed for collecting, transmitting, processing, storing, and showing information. Some examples are mobile phones, GPS devices, routers, personal computers, printers, and telephones.

2.3. Electronic waste (E-waste)

The Directive (EU) 2012/19 defines E-waste, also known as WEEE, according to their definition of waste in their Directive 2008/98/EC, which reads “any substance or object which the holder discards, or intends, or is required to discard” (2008, p. 9). This applies to all EEE and all components, sub-assemblies, and consumables which are part of the product at the time of discarding (Directive (EU) 2012/19, 2012). A simpler definition that attempts to bring clarity to the often subjectively viewed point at which EEE becomes waste reads “all types of EEE that have been discarded [i.e., thrown away or got rid of as useless] by the owner without intention of reuse” (stEP Initiative, 2014).

2.4. Small electronic devices

The term refers to EEE that, due to their small size and weight, can be disposed of in the general household refuse; these items can also be referred to as "bin-suitable", and many have been produced as not intended to be durable items, without upgradability and reuse in mind and are perceived as a heterogenous fraction difficult to dismantle (Dimitrakakis et al., 2009). Thus, small WEEE can be found in different categories of the Directive (EU) 2012/19. Main examples are small IT and communication equipment (e.g., mobile phones, game consoles, printers, keyboards, mice), screens and monitors (e.g., laptops, tablets) small equipment such as toys (e.g., car racing sets, music toys), household medical equipment (e.g., blood pressure meters), small household appliances (e.g. shavers, toasters, kettles, coffee machines, blenders, hair dryers, toothbrush) and others (e.g., cameras, headphones, remote controls, speakers) (Chancerel & Rotter, 2009; Dimitrakakis et al., 2009; Forti et al., 2020).

2.5. Materials in small electronic devices

Electronics have all classes of materials in their composition: polymers, ceramics, and metals; the diversity is related to the conferment of specific properties to the device for operation (Cenci et al., 2022). In general material fraction assessments, iron (Fe) and steel are the most common materials, accounting for at least 50 % of the products' weight, with plastic being the second largest fraction, followed by non-ferrous metals (Cenci et al., 2022). However, when focusing on small electronic devices the proportions change. Dimitrakakis et al., (2009) characterized 180 kg of small WEEE from municipal solid waste, and polymers made up the biggest fraction (more than one-third), followed by “electronic components” (a quarter), and then ferrous metals. They found PCBAs, “bonded” materials, and cables in smaller, but still important quantities (Dimitrakakis et al., 2009).

2.5.1. Plastics

Plastics, such as acrylonitrile butadiene styrene (ABS), polycarbonate (PC), polypropylene (PP), high impact polystyrene (HIPS), blend of PC and ABS (PC/ABS), and polyphenylene oxide (PPO), usually account for the housing, and casing of WEEE as well as the material for gadgets such as keyboards, while PE is usually found in cables and wires and PA in plugs, connectors and adaptors (Cenci et al., 2022). ABS appears to be the most common plastic in small WEEE, with a relevant presence in small household appliances (Dimitrakakis et al., 2009).

2.5.2. Metals

Base metals such as aluminum (Al), copper (Cu), Fe, manganese (Mn), magnesium (Mg), nickel (Ni), tin (Sn), and zinc (Zn), which are mainly present in the PCBAs and as part of casings or housing, make the metal fraction (Cenci et al., 2022; Cesaro et al., 2018). Platinum-group metals and precious metals like gold (Au) and silver (Ag) are common in PCBAs, and the latter (Ag) in connectors, chips, capacitors and lead-free soft solder as well, thanks to their chemical stability and conductivity properties (Cenci et al., 2022). Precious metals content in WEEE, however, has declined as a result of more compact designs (Cenci et al., 2022).

2.5.3. Rare earth metals and critical materials

Magnets and electronic components such as accumulators, electrodes, semiconductors, capacitors and electric contacts usually contain rare earth elements (REE) (Cesaro et al., 2018). Moreover, critical materials can be found in components such as lithium (Li) in batteries, antimony (Sb), cobalt (Co), niobium (Nb), titanium (Ti) in the housing or enclosure, tantalum (Ta) in capacitors and Sb, indium (In) and germanium (Ge) in PCBAs (Cenci et al., 2022).

2.5.4. Components requiring selective treatment and hazardous materials

The Directive (EU) 2012/19 forces member states to make selective treatment of at least some components, such as polychlorinated biphenyls containing capacitors, capacitors, batteries, mercury-containing components (e.g., switches), PCBAs, toner cartridges, plastic with brominated flame retardant, liquid crystal displays, asbestos-containing components, external electric cables, components containing refractory fibers, and radioactive substances (Directive 2012/19/EU, 2018; Salhofer & Tesar, 2011).

Many of the components requiring selective treatment contain elements that may result in direct environmental impacts if they are disposed of improperly. Incineration may produce toxic compounds, while uncontrolled landfilling may lead to leakages (Cenci et al., 2022). Even though many hazardous substances (e.g., lead (Pb), mercury (Hg), cadmium (Cd), and flame retardants) are restricted to maximum permitted concentrations (Directive 2002/95/EC or RoHs directive), it is broadly known that many of this substances are still present in WEEE coming from EEE introduced prior the enforcement of these restrictions (Cenci et al., 2022).

2.5.4.1. Printed circuit board assemblies

Printed circuit boards (PCBs) are a fundamental and common component in almost all electronic systems since they mechanically support and electrically connect the necessary electronic components (resistors, relays, capacitors, transistors, heat sinks, integrated circuits/chips, switches, processors, etc.) by fastening, usually using soldering or welding (Kaya, 2019; Nassajfar et al., 2021) to make up the so-called PCBA. High-value electronics (e.g., phones) use PCBs consisting of an assembly of different layers with a flame-retardant substrate, usually known as FR4, which is a composite material consisting of epoxy resin and woven glass fiber coated with layers of thin Cu film (Kaya, 2019; Kumar et al., 2018). Thus, all PCBAs have a nonconducting substrate or laminate, a conducting Cu substrate printed on or inside the laminate, and an electronic component attached to the substrate (Nassajfar et al., 2021).

The electronic components attached to the PCBs result in a mixture of multiple kinds of elements and materials, including ceramics, precious metals like Au, Ag, palladium (Pd), and platinum (Pt) in a higher concentration than their primary sources, heavy metals (Hg, Cd), rare elements like Ta, gallium (Ga), and flame retardants (Nassajfar et al., 2021). The relevance of selective treatment of PCBAs resides in preventing the dispersion of pollutants, especially those not yet restricted (e.g., Arsenic (As)), and the loss of precious metals (Salhofer & Tesar, 2011). Many of the electronic components are still functional and usable, and even in some cases, they are still in their optimal period of stable operation when PCBAs are discarded (Zhao et al., 2023). While the metal fraction is attractive for its value to be extracted, the remaining non-metal fraction, which accounts for almost 70 % of the PCB mass (e.g., glass fiber, cured epoxy resin, and impurities), is often discarded in landfills due to poor reuse and recycling alternatives (Kumar et al., 2018).

2.5.4.2. Batteries

Batteries are one of the main components of electronic devices and present several worrying facts, for instance, the presence of heavy metals and substances of concern in their electrolytes (e.g., lithium hexafluorophosphate) (Esquivel et al., 2017; Salhofer & Tesar, 2011) or their potential to cause fires and explosions in recycling facilities when they are not successfully handled and extracted (Torabian et al., 2022).

Today, lithium-ion (Li-ion) batteries are the most predominant energy source used for portable and rechargeable applications (e.g., mobile phones, laptops, digital cameras, etc.), which could be attributed to several advantages in their performance when compared to other common batteries (e.g., Ni-based): low self-discharge rate, high voltage (3.6 V), lightweight, good safety, and customizable shape (e.g., coin, pouch) (Esquivel et al., 2017; Liang et al., 2019).

Li-ion batteries consist of a graphite anode, a lithium oxide cathode (e.g., Li-Co oxides, Li-Mn oxides), and a Li salt serving as a liquid electrolyte or a polymer electrolyte in the case of Li-ion polymer batteries (Liang et al., 2019). The Li-ion battery upswing has raised concerns related to the extraction and availability of Li metal and others like Co, which are labeled as critical raw materials (Cenci et al., 2022; Esquivel et al., 2017; Windisch-Kern et al., 2022).

2.6. End of life routes for electronic devices

Forti et al., (2020), reported that WEEE is usually managed in one of the four following ways:

1. WEEE formally collected, meaning that it follows the requirements of national WEEE legislation, in which designated organizations, producers, and the government collect it. The destination is a specialized treatment facility that recovers materials, manages hazardous substances, and sends the residuals to incineration or controlled landfilling.
2. WEEE in waste bins, where the holder directly disposes of WEEE in "normal waste bins" with other types of mixed waste from households. In this scenario, the waste is most likely incinerated or landfilled; therefore, it is not treated appropriately. According to the authors, 8 % of global WEEE ends up in this scenario, and it is mainly comprised of the categories of small equipment and small IT (Forti et al., 2020).
3. WEEE collected outside of formal systems in countries with a developed waste management infrastructure. Within this scenario, individual waste dealers of

companies collect the WEEE. The destination for the WEEE may include metal and plastic recycling but most likely not depolluted as specialized recycling facilities do not treat them, and there is the chance for exported WEEE as well, which could end up in scenario 4.

4. WEEE collected outside of formal systems in countries with no developed waste management infrastructure. This scenario involves self-employed people engaged in the door-to-door collection to repair, refurbish, manually dismantle, and perform the so-called “backyard recycling”, where poor methods to burn, leach, and melt, take place to extract secondary raw materials.

From a more focused perspective, Baldé et al., (2020) reported for the Netherlands in 2019 that for the small equipment fraction 42 % was formally collected, 24 % was disposed of in the bin and later incinerated; about 30 % fell in scenario 3, and the rest is considered exported. For the small IT category, around 60 % was formally collected, about 16 % ended up in the bin and incinerated, and the rest, 24 %, was exported and potentially ended up reused in Eastern Europe or informally recycled in developing countries (Baldé et al., 2020).

According to Islam and colleagues (2021), end users are the starting point where WEEE begins its journey to different paths or strategies within the circular economy: (1) maintained or prolonged use, including sharing and repair; (2) reuse and distribution; (3) remanufacture and refurbishment; and (4) recycling.

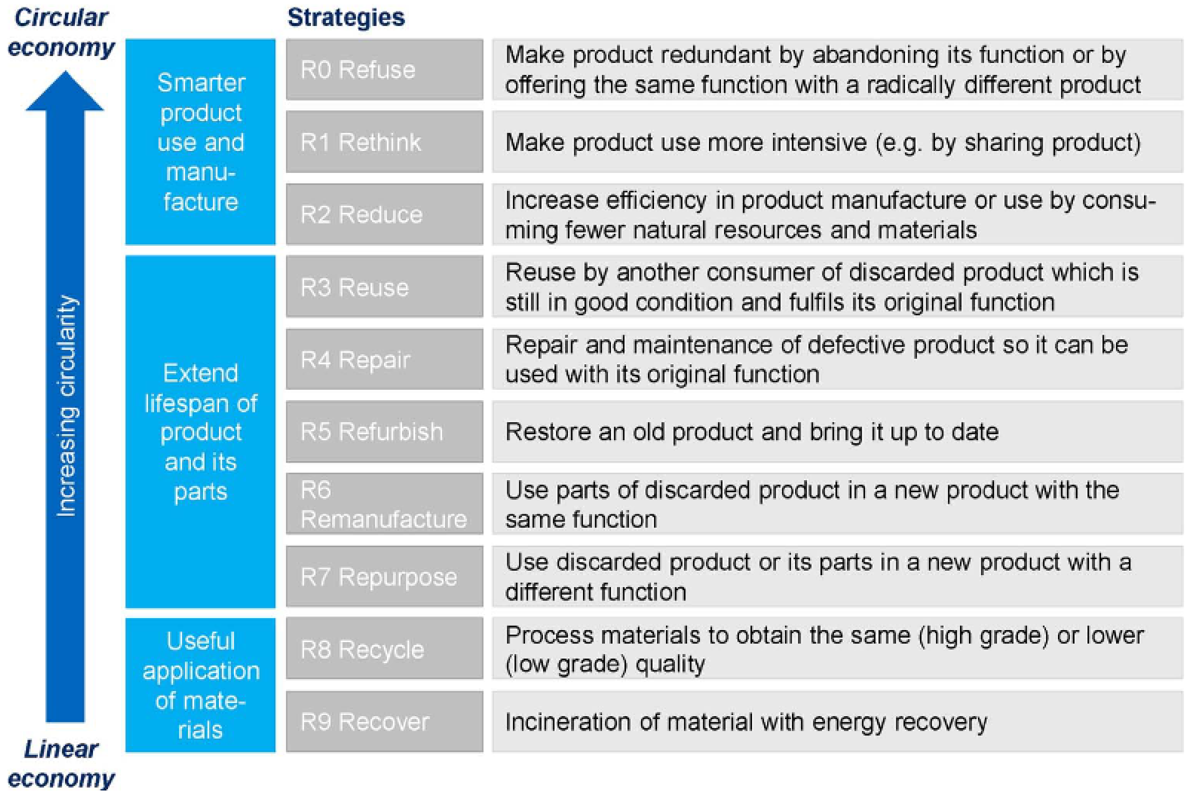
2.6.1. Reuse and repair

According to the 9R framework reported and adapted by Kirchherr et al., (2017) (Figure 1), both strategies belong to the category of “extend lifespan of the product and its parts”. Reuse refers to “reuse by another consumer of discarded product which is still in good condition and fulfills its original function” (Kirchherr et al., 2017). Repair implies “repair and maintenance of defective products so it can be used with its original function” (Kirchherr et al., 2017); thus, it is the correction of specified faults, and the quality of the repaired product is generally inferior to the refurbished or remanufactured alternatives (Goodship et al., 2019). Islam and colleagues (2021) reviewed the barriers to repair and reuse, and different authors found that, in general, users prefer to buy new mobile phones instead of repairing and reusing due to the higher repair cost; the high price is mainly due to the underdeveloped product-repair market considering the intentions of the manufacturers to obtain higher returns when selling new products. Additionally, product design and the lack of a market for secondhand items were mentioned as significant barriers.

2.6.2. Refurbishment and remanufacturing

Refurbishment refers to restoring an old product and bringing it up to date, and remanufacturing, on the other hand, uses parts of discarded products to make a new product with the same function (Kirchherr et al., 2017). The distinction between the two concepts is the warranty; remanufacturing implies that the resultant product has a warranty at least equal to that of a newly manufactured equivalent; a refurbished product (also known as reconditioned) instead has a warranty generally less than that of a newly manufactured equivalent (Goodship et al., 2019).

Figure 1. Circular Economy 9R framework



	Strategies	
Smarter product use and manufacture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1 Rethink	Make product use more intensive (e.g. by sharing product)
	R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
Extend lifespan of product and its parts	R3 Reuse	Reuse by another consumer of discarded product which is still in good condition and fulfils its original function
	R4 Repair	Repair and maintenance of defective product so it can be used with its original function
	R5 Refurbish	Restore an old product and bring it up to date
	R6 Remanufacture	Use parts of discarded product in a new product with the same function
	R7 Repurpose	Use discarded product or its parts in a new product with a different function
Useful application of materials	R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9 Recover	Incineration of material with energy recovery

Source: Kirchherr et al., (2017)

Both strategies also belong to the category of “extend lifespan of the product and its parts”. It is worth mentioning that “reuse and refurbishment represent the greatest value recovery opportunity from using devices as well as the most environmentally friendly step, which allows the material resources in the device and the embedded energy from manufacturing processes to be captured and reused" (Mars et al., 2016, p. 32).

2.6.3. Recycling

Recycling is at the bottom, preceding energy recovery strategy, of the scale of circularity according to the 9R framework, where "useful application of materials" takes place (Kirchherr et al., 2017). Waste recycling, according to the Waste Framework Directive, is "any recovery operation by which waste materials are reprocessed into products, materials or substances, whether for the original or other purposes […]" (Directive (EU) 2008/98/EC, 2018).

Generally speaking, recycling of WEEE starts with its collection, following, for instance, the six EU categories (Feenstra et al., 2021). Then it moves to the pre-treatment step, where manual or mechanical dismantling opens the assembled products to collect and separate hazardous and valuable components such as batteries, capacitors, toner cartridges, electric motors, PCBAs, or impurities (Cenci et al., 2022; Feenstra et al., 2021), to prevent them from continuing to the following steps and ensure proper treatment. This sorting step may happen manually with trained staff next to conveyor belts (Maisel et al., 2020). Shredding, which is the process of reducing the size of the remaining parts, is subsequently performed to liberate ferrous, non-ferrous, and plastic materials, which later undergo physical processing to separate and concentrate the compounds in different fractions by means of magnetic, current-based, or density separation techniques (Ahirwar & Tripathi, 2021; Cenci et al., 2022; Feenstra et al., 2021).

Metals are recovered using hydrometallurgical and pyrometallurgical processes. The former uses methods such as solvent extraction and leaching to selectively dissolve precious metals and later recovers them from the effluents through electrorefining or chemical reduction processes (Ahirwar & Tripathi, 2021); however, this method implements hazardous reagents (e.g., strong inorganic acids) and generates toxic and delicate effluents and sludges (Cenci et al., 2022). Pyrometallurgical methods are harnessed in thermal treatment and, thus, can accept several forms of scrap; they are usually used for initial segregation and are usually followed by hydrometallurgical methods since they are not as selective as the others, and thus, losses of precious and critical metals occur (Ahirwar & Tripathi, 2021; Cenci et al., 2022).

It is worth noting that components such as the PCBA follow a similar approach for their individual recycling process as they generally undergo manual dismantle of easily removable electronic components which then are separated for reuse; the remaining materials move to shredding, crushing, and pulverizing to granulate them in fine particles (Chakraborty et al., 2022). Then it moves to different separation processes to separate metal fractions from non-metals and finally moves to the crucial leaching step (i.e., hydrometallurgical process) where precious metals are extracted (Chakraborty et al., 2022). However, the purity and recovery rate of material from PCBAs recycling processes remain inefficient and a topic of concern (Canal Marques et al., 2013; Copani et al., 2019).

The plastic fraction is further sorted into pure polymer fractions such as PP, PS, ABS, etc. Flame-retardant flakes are ruled out and incinerated (Feenstra et al., 2021). Accurate sorting by resin is crucial to achieving high-purity recycled materials; nowadays, waste-sorting facilities have in place optical sorting methods like near-infrared (NIR) reflectance spectroscopy and NIR hyperspectral imaging spectroscopy to classify plastic waste based on their spectral signatures (Rozenstein et al., 2017). Other common sorting methods, like density sorting or flotation, may also take place (Maisel et al., 2020). Cleaning and preparing for compounding into pellets is the latest step for this fraction (Feenstra et al., 2021).

Mars and colleagues (2016) stated that recycling electronic devices faces several challenges closely related to logistics and costs that make economic viability a threat to their business models. Some of the main challenges are the transportation costs of WEEE and recovered material and the high rate of evolution of electronic devices, which brings uncertainty to recyclers on how to adapt their processes and forecast to create robust planning. Additionally, designs like “integrated batteries” lead to labor-intensive and time-consuming disassembly, causing monetary losses (Mars et al., 2016). “Devices reaching the end of life become smaller and lighter and therefore less valuable for materials recovery” (Mars et al., 2016, p. 32); Mars and colleagues also reported that, for instance, PCBAs in the market are reducing the amount of precious metals, and coupled with the fact that WEEE recycling is dependent on commodity prices, especially precious metals, that could make disassembling the device and transporting the recovered material more costly than the actual selling of the material recovered (Mars et al., 2016).

2.7. Sustainability and green electronics

The terms “sustainability” and “sustainable development”, usually used as synonyms, have become a reference for scientific research associated with the environment (Ruggerio, 2021). The definition of sustainable development given in the report “Our Common Future” by the Brundtland Commission in 1987 reads “[…] development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (United Nations, 1987); it has served as a starting point to define research on sustainability. That is the case for many authors in the field of sustainable electronics (Gurova et al., 2020; Scandurra et al., 2023; Tischner & Hora, 2019) who refer to this definition in their works. The definition commonly employs three dimensions: economic, social, and environmental. In this regard, some studies, when addressing sustainability, may refer to a specific line or a combination of the three (Alhaddi, 2015).

Design for sustainability (DfS), due to its *umbrella term* nature, deals with the three dimensions of sustainability, and stresses the importance of not only relating it to green/eco-design or design for recycling, which focuses on environmental and economic aspects but also in humanitarian and social design (Tischner & Hora, 2019). DfS harnesses life cycle thinking and system perspective, which takes into consideration all phases of the product life to identify the correct priorities, that is, "the most important sustainability aspect;" and solves it from different stages in the product’s life cycle (Tischner & Hora, 2019).

In a very simplified way, Tischner and Hora (2019) use as an example a T-shirt, where "the most important sustainability aspect" could be the extreme use of pesticides (environmental and social concern) during the raw material production and the hard-working conditions (social concern); thus, DfS would attempt to improve the environmental and social consequence by recycling cotton fibers into new T-shirts to eliminate the negative impacts of cotton production from the life cycle.

Authors (e.g., Gurova et al., 2020) acknowledge that the field of sustainable electronics could create effects in the three dimensions, for example, in the social dimension through the role of electronics in the improvement of people’s well-being and quality of life (Lee et al., 2016); however, the environmental line receives particular attention mainly due to the increase in the demand for electronics in many sectors of life plus their relatively short life cycles and ultimately their concerning material composition (Forti et al., 2018; Gurova et al., 2020; Scandurra et al., 2023) which resulted, as Cenci et al., (2022) described, in increasingly rigorous environmental legislations to alleviate the environmental pressure and thus the increase in eco-friendly sought devices.

Hu & Ismail, (2011) offer a comprehensive definition of eco-friendly or green electronics, which covers four different perspectives:

1. Green manufacturing: processes that are environmentally friendly and do not create or involve hazardous materials or chemicals.
2. Green disposal: advanced product design with cleaner materials, longer product life, reduction of electronic waste (e-waste), and the introduction of programs to incentivize reuse and recycling, considering that electronic devices consist of valuable resources that require considerable energy to process and manufacture.
3. Green use: aiming for energy efficiency in electronic devices during use, like powering down devices during inactivity.
4. Green design: innovative designs and techniques to reduce energy consumption, carbon emissions, and e-waste disposal.

From this characterization and an extensive analysis Cenci et al., (2022) built on the definition of green electronics as:

> electronic equipment that directly or indirectly have a net positive impact on the environment compared to their alternatives. This goes beyond the manufacturing and recycling process – it includes the purpose of different electronics (their function, what they are used for), the materials contained therein, the waste generation (or avoidance thereof), and ease to manage their EoL (whether in terms of recycling, reusing disassembling, repairing, etc.). (p.26).

Literature addressing the topic of green and sustainable electronics (e.g., Cenci et al., 2022; Tischner & Hora, 2019) gives attention to alternative materials and components that require less resource input or with superior “eco-properties” such as biodegradable materials, upgradable and reusable electronic parts, recyclability or durability. Additionally, the manufacturing process of EEE pays special attention to the design phase, where concepts such as “design for End-of-Life” are strongly encouraged. The following sections explore the state of the art on two strategies for green electronics, materials with superior eco-properties and Design for X framework.

2.7.1. Materials with superior eco-properties

There is a pressing need for material selection in electronic devices in terms of toxicity, abundance, and recyclability, which translates into efforts to find substitutions for less noxious materials in electronics. These alternatives often consider materials that require less resource input during manufacturing or properties like biodegradability, recyclability, or durability (Cenci et al., 2022).

For instance, Cenci et al., (2022) reviewed advances in substitutes for metals and REE in electronic devices. They found that the biggest challenge in this material category is that “substitution often results in reduced performance” (Cenci et al., 2022). That is the case for Ga, a critical raw material that is widely used in semiconductors. It provides unique properties in terms of speed and energy consumption that hinder its replacement with alternative materials (Cenci et al., 2022). Nonetheless, there are more optimistic substitutes; for instance, in the field of conductive inks for electrode printing (e.g., for flexible sensors), there are promising efforts in graphene-based ink to substitute Ag ink (Benwadih et al., 2014; Zappi et al., 2021).

In response to the increasing demand for Li batteries, Zn-air chemistry batteries are gaining momentum as an alternative to them thanks to their larger energy density, lower cost, and safety (Santos et al., 2020; Zhang et al., 2019). Additionally, “because of its abundance, geographical dispersion, and lower cost than lithium, zinc is appealing as a vital battery material” (Alemu et al., 2023). Zn-air batteries are currently widely used for powering hearing aid devices owing to their low power output (Mir et al., 2023). However, the main drawback of this technology compared to Li batteries and where efforts are focused is related to rechargeable Zn-air batteries, as they have poor cycling stability and limited energy density (Zhang et al., 2019).

Innovative approaches exist with biodegradable batteries in the literature where materials are replaced with the so-called biodegradable metals such as molybdenum (Mo), Fe, or magnesium (Mg) one of the main drivers for this kind of technology is the need for biocompatible materials for developing biodegradable sensors for clinical applications (Hosseini et al., 2021). Karami-Mosammam et al., (2022) developed a flexible biodegradable battery consisting of a molybdenum trioxide paste as a cathode, a Mo foil as a current collector, and a Mg foil as anode; they made the enclosure and backbone of biodegradable polymer poly(glycerol sebacate) (PGS). The battery could power a sensor patch for several hours.

Esquivel and colleagues (2017) proposed a metal-free battery using only organic materials such as cellulose, carbon paper, and beeswax, which uses a quinone-based redox chemistry activated by a liquid sample that dissolves the reactants and carries them to the electrodes to generate electricity. The battery can operate for short periods of 100 min, and the output voltage can be tuned by stacking several cells to achieve the usual voltage of 3 V needed for portable electronics (Esquivel et al., 2017). The most attractive feature is that according to their biodegradability test results, it could be disposed of in soils and water, eliminating the need for recycling.

As mentioned before, some biodegradable polymers, like PGS or cellulose, are posed as an option for green electronics; however, one of the shortcomings of biodegradable polymers in the field of electronics is the lack of thermal and chemistry resistance needed to resist the production process of the devices (Cenci et al., 2022). Biobased polymers have the potential to reduce the carbon footprint associated with the electronic device (Cenci et al., 2022). Poly(lactic acid) (PLA), for instance, is a cost-effective option while being biobased and biodegradable (European Bioplastics, 2022); nonetheless, the latter requires industrial composting with temperature control to support rapid decomposition (Meyer & Katz, 2016). Cenci and colleagues (2022) reported that the addition of certain substances can enable PLA to be utilized in the production of compact disks, computer cases, and cellphone cases. Van Den Oever & Molenveld, (2017) tested the technical feasibility of bio-based polymers to replace fossil-based cover panels of an electronic device and determined that PLA compounds with a bio-based content as high as 85 % can replace bulk polymers like polystyrene.

Another area that has received particular attention about polymeric materials is wearable and stretchable electronic devices (Cenci et al., 2022). Polymeric materials are tunable, flexible, and biocompatible; thus, they are of interest to be used as substrates to provide an electrically inert foundation for the deposition of multiple functional materials like dielectric layers, semiconductors, and conductive electrodes (Hosseini et al., 2021). Substrates are crucial as they determine the device's stability and degradation; moreover, they tend to constitute most of the device's weight, generating most of the waste (Hosseini et al., 2021). Linked to this principle, a focus on silk, chitosan, cellulose, and other natural-based polymeric substrates has been made in the literature (Hosseini et al., 2021).

Regarding printed circuit boards, the environmental concerns around the glass-fiber reinforced epoxy substrate of common PCBAs have led researchers, such as Liu and coworkers (2014), to explore the concept of paper-based electronics. They prototyped a paper-based multilayer PCB, which resulted in lowering two orders of magnitude the environmental impact compared to a common PCB in a LCA study. Mattana et al., (2015) proposed a substrate made of spin-coated PLA thin films, which exhibited similar mechanical properties to commonly used substrates for PCBAs. More recently, Immonen et al., (2022) examined the potential suitability of wood-based materials, such as cardboard and veneer, as a substrate for PCB; they determined that the latter is more screen-printing friendly than cardboard, but “more research is needed on substrate surface treatments and application-focused design related to the replacement of etching processes with screen printing before actual wood-based PCB products can be available” (2022).

Chakraborty et al., (2022) also reported on biodegradable substrates for PCBAs and the need to improve mechanical and thermal stability, dissolution, and the ability to withstand harsh environments. Besides, they comment on the increasing interest in conjugated polymers and conductive nanocomposites – although not always degradable - to substitute conductive materials needed for the tracks (usually made of Cu and Ag); additionally, Mg and Mo have also been explored as electrode-dissolvable options. They also commented on prospective options for biodegradable semiconductors made of silicon nanomembranes, metal oxides (e.g., zinc oxide), and a new class of semiconducting polymers (Chakraborty et al., 2022). On the side of PCB manufacturing, copper-etched fabrication may start seeing a replacement due to the advancing research on printing electronics technologies (Chakraborty et al., 2022).

2.7.2. Design for X: guidelines

In recent decades, the scientific literature has broadly discussed the frameworks of “design for X,” where X represents different approaches, like “the environment,” from which further distinctions derive: design for disassembly, design for recycling, design for EoL, etc. (Berwald et al., 2021). For instance, Martínez Leal et al., (2020) use the term “design for material recovery” to describe the modifications in a product to increase recovering potential and regenerate its materials based on the knowledge of EoL processes and performances. Similarly, Rifer & Brody-Heine (2009), noted that many eco-labels, for example, the environmental standard for the Electronic Product Environmental Assessment Tool (EPEAT), incorporate criteria addressing the relationship between product design and EoL, giving relevance to the design for end-of-life approach. The relationship between designers and EoL routes is usually translated into design guidelines that aim to guide designers to make choices that will ease the EoL of the products (Martínez Leal et al., 2020; Talens Peiró et al., 2017).

Martínez and colleagues grouped several of these guidelines into seven categories according to two different scopes: design choices and transmission of information – to the different stakeholders involved in the product’s EoL to make the treatment process more efficient. The former pays attention to the fasteners, products, components, and materials – and with minor relevance to cables and connectors. On the other hand, the transmission of information focuses on marking and labeling information. Bovea & Pérez-Belis, (2018) did a similar job with what they denominated “design guidelines that focus on the circular economy,” where they compiled a set of guidelines grouped in the categories of extension of life span, disassembly – which divided into connectors and product structure –, product reuse, components reuse, and material recycling.

2.7.2.1. Design for disassembly

Disassembly is a central point of the design guidelines, as Bovea & Pérez-Belis included in their classification, as well as for the scope of design choices, especially for fasteners, products, and components presented by Martinez and colleagues. Design for disassembly (DfD) is widely mentioned in the literature for green electronics (Cenci et al., 2022); it seeks that the equipment design facilitates or enables its disassembly when its useful life ends with the goal of recovering materials and components; thus, DfD is crucial for repair, reuse, and recycling to contribute to the circular economy thinking where valuable resources are conserved and kept longer (Cenci et al., 2022; Shahhoseini et al., 2023; Talens Peiró et al., 2017). Disassembly operations consist of component separation, making a product keep its intrinsic properties, while destructive procedures ignore the latter consideration (Talens Peiró et al., 2017).

Fasteners, connectors, or joints are key for DfD. They form a relationship between two components, and they pretend to restrict their movement within an assembly (e.g., securing the device enclosure, fixation of the battery, elements mounting, etc.); thus, they have a key influence in the separation and disassembly of components, and while certain joining processes can facilitate rapid fabrication they could compromise, for instance, the repairability (Schischke et al., 2013; Talens Peiró et al., 2017).

Many authors have compiled strategies and recommendations around the topic of fasteners and disassembly (Berwald et al., 2021; Rifer & Brody-Heine, 2009; Talens Peiró et al., 2017; Tischner & Hora, 2019). Many guidelines regarding fasteners focus on the complexity of the fastening systems and their diversity, identifiability, accessibility, durability, disassembly, and the tools needed to remove them (Martínez Leal et al., 2020). Thus, they encourage reversible solutions like screws, clips, or snap-fit solutions and de-recommend permanent solutions such as glue or pressure-sensitive adhesives (PSA) (Berwald et al., 2021).

Regarding the device architecture, Martínez Leal et al., (2020) mention guidelines concerning, on the one hand, the complexity, modularity, and overall disassembly of the product; on the other hand, the identifiability, accessibility, and disassembly of components containing non-recyclable, toxic, precious and critical materials.

Modular design is a recurrent guideline (Bovea & Pérez-Belis, 2018; Martínez Leal et al., 2020; Talens Peiró et al., 2017) which refers to a product architecture that requires less effort to change components compared to an integrated structure, offering the possibility of exchanging single parts and not necessarily the whole product for a change in the product (Hankammer et al., 2018); thus, modularization of product structure is an aspect of the improvement of product reusability and recyclability.

Related to this concept is “technology modules” which recommend grouping components with the same retirement methods (disassembly, recycling, and disposal) in the same module (Chun-Chen Huang et al., 2011). Berwald et al., (2021) focus on several guidelines related to components under the general statement of “enabling easy access and removal of hazardous or polluting components” and suggest “a module for hazardous components” that enables the removal of a single part containing all the non-recyclables and detachment possibilities for polluting materials such as textiles, foams, dust bags, cord sets, etc.

Bovea & Pérez-Belis, (2018) identified that “facilitate the accessibility of essential components” is a recurrent guideline, which is in line with what Schischke et al., (2013) found when conducting disassemble studies in tablets where in order to access a critical component (e.g., battery), they had to remove smaller parts such as camera, cable, tapes, or electromagnetic (EMI) shields until they get to the desired item.

2.7.2.2. Design for recycling

Design for recycling considers that the initial design of EEE is crucial to meeting the recycler’s feedstock requirement (Berwald et al., 2021). The increasing complexity of WEEE explains the need for these guidelines, especially the plastic mix, which makes it more challenging to recover all the different polymers even with advanced recycling technologies (Berwald et al., 2021).

These guidelines focus on facilitating the identification, recyclability, separation, and compatibility of the materials (Bovea & Pérez-Belis, 2018; Martínez Leal et al., 2020). Berwald and coworkers (2021) created a comprehensive set of guidelines focusing on “design for recycling.” One section focuses on recyclable materials; it emphasizes the materials to avoid, such as foams, thermosets, composites, and material combinations - discouraging molding different materials together -. In line with material combinations, Martínez Leal et al., (2020) went a step forward and discussed compatibility and diversity. The former addresses the chemical compatibility between two different materials, where two materials are incompatible if the properties of the material to be recycled decrease if both are recycled together. Diversity assumes that a greater variety of materials makes harder the recycling process.

Interestingly, many of the guidelines given by Berwald and colleagues for design for recycling came from the “design for disassembly” owed to the importance of the pretreatment phase, where recyclers must remove hazardous components; thus, they emphasize the accessibility and fasting methods to fix components such as batteries and PCBAs.

Chapter 3. Methodology

3.1. Research background and scope

This research begins in the context of an internship that took place from May 2023 until September 2023 in the department of manufacturing and operations of a company that designs and manufactures a small electronic device for at-home sleep diagnostics and monitoring to conduct polysomnography tests.

The device (from now on, “sleep device”) consists of a multilayered adhesive patch-base sensor connected to a small pod containing the electronics. The internship project focused on researching sustainable solutions by analyzing published information from research institutes, universities, and commercial companies. The objective was to identify sustainable innovations and best practices for the disposal, recycling, and reuse of similar medical devices and provide recommendations. The exploration considered a single-use scenario – patients dispose of the device after the study – and a return scenario – patients send back the device to the company after the test –. In the context of exploring solutions within a company seeking tangible results, the maturity and feasibility of these solutions were crucial factors that narrow the selection of proposals derived from the research.

During the literature review, two different approaches for green electronics proved to have a substantial relevance for the topic: materials with superior eco-properties and design for the EoL. Following the definition given by Cenci et al., (2022) on green electronics, depicted in the literature review, these two approaches bring, allegedly and directly or indirectly, net positive impacts on the environment in different aspects of the life cycle of the electronic devices, which also answers to the sustainability question. Nevertheless, when contrasting the two approaches with the necessity for manufacturing teams to have ready-to-use solutions, the existing body of literature leaves room for enhancement and refinement. The following section depicts the justification and methodology to delve into both approaches.

3.2. Components with superior eco-properties

The literature review underscored an increasing interest in developing and implementing materials with superior eco-properties in components and parts for electronic devices to respond to the need for greener electronic devices. However, there is a notable disparity between the theoretical advances showcased in laboratory settings and the pragmatic necessities of companies, as the latter cannot work with not-available solutions.

In this section, the sleep device served as the focal point for identifying key sustainability concerns related to its components. Consultations with various company members highlighted the PCBA, battery, and patch as major areas of interest. The two former components were also recurrent topics in the literature, particularly concerning hazardous elements and materials requiring special treatment. Given their significance, the exploration concentrated on the PCBA and battery. Additionally, the focus extended to the patch due to its prominence in similar devices, and advancements in biodegradable substrates highlighted during the literature review in studies like those by Hosseini et al., (2021).Throughout the exploration, incidental discoveries involving components beyond the initial focus were considered. Within the selected scope, referring to "components" rather than "materials" was the logical choice.

Criteria to identify potential solutions are centered on the maturity of the option or, in other words, the feasibility of the company to incorporate the component in the manufacturing of the sleep device. Therefore, the exploration prioritized commercial suppliers.

In a first general inquiry with the research engine Google used keywords such as *sustainable*, *green*, *eco-friendly*, *environment*, and *biodegradable* next to the words *electronics*, *wearable devices*, *electronic components*, and *small electronic devices*. Then, the method followed more specific inquiries using the words related to sustainability with the Boolean connector AND next to the components phrased in several manners:

- For the PCBA: printed circuit board, printed circuit board assembly, PCB, PCBA
- For the battery: batteries, batteries for wearable devices, disposable batteries, energy cells, coin cell batteries
- For the patch: adhesives for medical assemblies, tapes, wound care, adhesive substrates, inks, and electrodes.

Options from commercial suppliers were identified for the three components, and information was primarily gathered from open documentation on their websites. In-depth discussions were held with PCBA and medical adhesive suppliers via online meetings to gain detailed insights into their solutions.

3.3. Design guidelines

Design guidelines within the frameworks of “design for X” in the literature have arisen as a tool to fill the knowledge gaps that designers have on EoL processes and their complexity (Fakhredin et al., 2013; Martínez Leal et al., 2020). Fakhredin and colleagues (2013) argued that the problem with these “heuristic guidelines” is that they are very product-specific and too generic, which makes it hard to prioritize the rules with the highest impact on design. More recently, some authors have tried to tackle these problems. For example, Bovea & Pérez-Belis, (2018) evaluated several design guidelines from a circular perspective to identify the most important ones to accomplish circular principles in a design. On the other hand, Berwald et al., (2021) used a more multi-stakeholder approach across the entire WEEE value chain, with a focus on recyclers, to provide practical and up-to-date guidelines. The former work acknowledges a limitation on subjectivity when assessing the parameters that their methodology uses. The latter stresses the constant evolution of materials and processes and the need for updates; moreover, it underscores the opportunity for cluster-specific guidelines for WEEE categories.

Therefore, selecting design guidelines for small electronic devices and delving into the nuances of design guidelines contributes to a fresh and updated perspective in the field, which is not only helpful in practical terms for designers but also for other research works attempting to hone this line of work.

In the case of this exploration, for the process of formulating a comprehensive set of design guidelines, two distinct works, Bovea & Pérez-Belis, (2018) and Martínez Leal et al., (2020), that had compiled extensive guidelines from the existing literature were meticulously analyzed. The methodology involved identifying guidelines mentioned in both works to ensure the integration of consistent insights. Guidelines unique to one author were carefully evaluated to assess their relevance to the overall themes. If a guideline was found to be ambiguous or lacked specificity and self-explanatory context, it was disregarded. To avoid redundancy, similar guidelines from both authors were merged into one consolidated guideline. They were classified into four main categories: fasteners, design architecture, material recycling, and others. Each guideline was assigned a short code for easy reference during discussion.

Remarks from the works of Berwald et al., (2021); and Schischke et al., (2013) accompany some guidelines, as they bring a more practical and multi-stakeholder perspective. These remarks aim to provide more specific details on the “how” of some guidelines that, by themselves, may lack this aspect. For Berwald and colleagues, the multi-stakeholder approach that they followed has already been introduced and proved to be relevant. Schischke et al., on the other hand, show to be pertinent as they conducted a disassembly analysis on different tablets. In their study, they quantified the type and number of screws, clips, adhesives, connectors, and tools needed to open 21 different slates. They considered the following steps: (1) open the tablet, (2) remove the battery, (3) dismantle the main board, and (4) dismantle the remaining parts (e.g., the display unit). They took two different approaches: disassembly for repair and refurbishment—avoiding destructive removal and possible replacement of main subassemblies—and disassembly for commercial recycling—focusing on fast and economical disassembly with the aim of battery removal.

Lastly, some remarks from disassembly videos are included. These public access videos belong to iFixit, a big advocacy company of the Right-to-Repair movement with an online resource community-driven platform that provides repair guides and step-by-step teardown instruction videos for a wide variety of electronic devices. The relevance of this material to this exploration is to visually sense the nuances of the disassembly processes.

3.3.1. Interviews

Following a similar approach as Berwald et al., (2021) interviews were conducted to further elaborate on the remarks of the design guidelines and mainly discuss their relevance for the different interviewees. Three interviews were conducted with different EoL handlers. The selection of the interviewees is supported by the design for X frameworks associated with the design guidelines, and the circular EoL Islam et al., (2021) reported that electronic devices usually follow. In this regard, WEEE recyclers were an evident choice, but also people in the field of repair and refurbishment of electronic devices when considering the return scenario of the sleep device.

For privacy, from now on, the work refers to the interviewees as the repairers, the manual recycler, and the automatic recycler. The description of each of them below justifies their selection based on their relevance to the topic:

- The repairers: Two participants from a prominent advocacy company specializing in electronic device repair contributed to this interview. One member has extensive experience advocating for right-to-repair legislation. The other has a background in collaborating with manufacturers to establish effective “repair ecosystems,” ensuring the feasibility of repair processes for electronic devices within companies.
- The manual recycler: the interviewee was the co-founder and current advisor of a company specialized in the proper disposal and management of electronic equipment in a major metropolitan city. This expert possesses extensive experience in disassembling electronic devices and preparing them for recycling. This process includes tasks such as harvesting parts for remanufacturing, tearing down WEEE, manual separation of various components into different material fractions, and removing hazardous materials for safe recycling.
- The automatic recycler: This interviewee is employed at a WEEE recycling company, handling large volumes of waste. Unlike the manual recycler the process only involves manual shredding preparation – removal of the battery, cables, and other hazardous materials – but then the company relies on advanced technology to sort different material fractions efficiently and at great scale.

The individuals interviewed for this study encompass a diverse range of expertise in the electronics repair and recycling industry. On the side of recyclers, two very different approaches for recycling WEEE enrich the conversation regarding this EoL. The three interviews were conducted online with a one-hour duration. It used a semi-structured format, allowing the EoL handlers to freely share their experiences and insights. Participants were informed in advance via a questionnaire about the general topics related to design guidelines aimed at assisting designers in modifying devices to enhance their EoL handling. During the interviews, the handlers spontaneously discussed relevant design guidelines from their perspective and challenges. Not-mentioned guidelines were introduced to prompt discussion and evaluate their applicability. Furthermore, insights shared during the interviews were categorized and integrated into the design guidelines most pertinent to the respective points, enhancing their comprehensiveness and depth them.

Additionally, aligning the design guidelines with the feedback from the interviewees was a deliberate strategy to facilitate a more systematic analysis and discussion of the interview contents. This integration, along with the additional insights derived from other literature sources mentioned earlier, aims to enrich the overall depth and context of these qualitative findings.

Chapter 4. Results and discussion

In this chapter, the results and discussion are presented using a descriptive approach, allowing for an in-depth exploration of the themes, patterns, and insights derived from the data sources. The findings will be delivered in narrative while discussed. Additionally, to enhance clarity and facilitate easy comparison, key points and significant themes will be summarized in tables.

4.1. Components with superior eco-properties

Table 1. displays a summary of the different solutions found during the supplier exploration. Features giving superior eco-properties to the solution are also provided.

Table 1. Summary of supplier solutions

Component	Solution by suppliers	Superior eco-property
PCBA	Unzippable PCBA	▪ Less impactful manufacturing. ▪ Easy recovery of electronic components from the substrate.
Battery	"Safe and environmental" sound battery	▪ Nonhazardous materials
	Biodegradable bio-fuel cell	▪ Biodegradable
Patch	Solventless adhesives	▪ Low level of volatile organic compounds
	Plastic like recyclable substrate	▪ Printed electronics recyclable with no special treatment
	Biodegradable substrate	▪ Degrades on soil liberating mounted components.
PSA	Reworkable PSA	▪ Easy removal with no residue

4.1.1. Printed circuit board assembly

PCBAs contain a large portion of the most valuable resources within SEDs, as described in the literature review. They additionally tend to support the most expensive and crucial components of the device, like microchips, which are pretty much the brain inside the EEE. Consultation with members where the internship took place showed that there is an environmental and economic interest to reuse PCBAs to address those two aspects. Zhao et al., (2023) support this method, claiming that many researchers have shown that in some cases, reusing PCBAs in certain household appliances results in lower environmental impacts compared to new EEE and can yield better economic benefits.

Reuse of PCBAs looked like an alternative if there was a return scheme of the devices in place, the latter being out of the scope of this research. In this way, manufacturers can reuse the PCBA in remanufactured items, extending the useful life of electronic components. It does not seem problematic to use the whole assembly when it returns entirely functional. The challenge, however, for manufacturers is when repairing, swapping, or tunning the PCBA is needed. As described in the literature review, electronic components are soldered to the substrate, making disassembly difficult. For reclaiming them, the first step is melting the solder joints (Zhao et al., 2023); the drawbacks of this step are that desoldering methods tend to be inefficient and not suitable for industrial applications (Wang et al., 2016). Secondly, the disassembly itself mainly consists of applying external forces that could potentially harm or destroy the electronic components during the operation (Zhao et al., 2023).

In contrast to all these drawbacks, supplier exploration found a potential solution. A sustainable electronic company offers unzippable PCBAs that overcome the obstacles of reclaiming electronic components from the substrate. An interview with the *sustainable ambassador* (SA) from this company explained how hot water and mechanical forces weaken the shear bond strength. Hence, the reclamation of metals, substrates, and components is feasible for a second life.

From an environmental perspective, the unzippable PCBA has a manufacturing process considerably less impactful than common FR4 PCBAs. The SA presented a case study where the carbon dioxide equivalent (CO_2e) reduction was 62.5 %. The technology, reportedly, enables manufacturers to reuse the entire assembly when no fault is present and easily swap a faulty part if needed. The unzipping process can be carried out by the manufacturers with previous instructions from the technology creators or outsource this operation to the company in question (SA, personal communication, 2023). Additionally, the technology, reportedly, offers design flexibility to meet manufacturers' expectations, for instance, with rigid, semi-rigid, and flexible substrates. However, EoL handlers cannot be expected to know how to exploit the virtues of such PCBAs, as they are not widely spread, limiting, at the moment, recycling to the OEM and supplier.

4.1.2. Battery

During the internship and supplier exploration, it was relevant to compare the kind of batteries that single-use medical electronic devices use. These SEDs have in common being wearable and monitor different patient vital signs, so many of them come in the form of patches. Four devices use coin-like batteries, of which two used Zn-air chemistry (1.4 v), and the other two were Li-coin batteries (3 v). From the former, one of the devices uses a combination of two-coin Zn air batteries. An interesting aspect is that the obsolescence of these single-use devices is closely related to the useful life of the batteries. The user manuals of these devices suggested that the device will stop functioning once the battery ran out. Two devices lasted for seven days, and the other double. It is worth mentioning that there is no evidence to believe that the rest of the components in the device would stop working as well. One device was found to be independent of the battery's useful life as it was powered by a single-use AAA alkaline battery. Patients are advised to reuse the alkaline battery in other appliances as it is easily accessible and dispose of the remaining electronics.

This short exploration, contrasted with the environmental challenges exposed in the literature review, proves the necessity for designers to have available disposable batteries whose impact on the environment is lower. Two different suppliers were found to be aligned with this; nonetheless, the reported information is limited to what their websites included since no interviews were possible to set.

The first battery company (FBC) is developing a battery with safety and environmental impact in mind, using no hazardous materials. The website states that they plan to offer two types of batteries: a more environmentally conscious and safety-oriented type and a high-power, long-lasting type. The former uses Zn-air chemistry and is free of Hg, Pb, Cd, Li metal, potassium hydroxide (KOH), and flammable organic solvents. The latter uses a Mn-Zn chemistry with no strong alkaline electrolyte in the battery. It is expected to have a capacity and energy density two to five times higher than an Mn-Zn sheet battery with a typical aqueous electrolyte solution. Their voltage is 1.2 V, and different sizes deliver a range of capacities and discharge currents; they offer a flat and flexible shape ideal for powering medical and healthcare patches, logistic control tags, and wearable and disposable devices (FBC, 2023).

The second battery company (SBC) offers a paper biofuel cell whose more attractive feature is that it is compostable. Mainly consisting of cellulose and carbon, the cell is metal-free. The biofuel cell voltage is 0.75 V, and it cannot compete with Li-based batteries in terms of power or energy density. Thus, it is ideal for single-use and short-operational lifetime electronics such as tracking systems, wearables, and single-use medical tests (SBC, 2023).

It should be noted that both options are not ready-to-use solutions. The former is still developing this solution, and the drawbacks of the latter would need a closer look to understand whether the solution is suitable for the device requirements.

Consultancy with the electronic engineer of the company where the internship took place disclosed the importance of the shape factor of the battery in the design of the device. In this specific case, the battery shape and size determined not only the overall dimension of the device but also the device's performance when detecting the signals during the monitoring procedures. The form of the batteries described before would require designers to rethink the whole architecture of the device. This aspect proves the necessity for designers to have more sustainable component options and consider, in advance, the options available before building the device structure.

Rechargeable batteries arose as a consideration during the internship in the scenario that the sleep device returns. It should be noted that this study did not thoroughly assess or demonstrate the environmental benefits of rechargeable batteries over disposable ones; however, the consideration built on the reuse principle of rechargeable batteries, which could slow down the impacts associated with disposable batteries, as long as a minimum number of charge cycles is reached (Dolci et al., 2016). Thus, quantitative assessment would be needed to find the correct number of uses. Moreover, designers should foresee legal limitations in certain components; in 2022, the European Parliament announced that by 31 December 2030, the Commission will assess whether to phase out the use of non-rechargeable portable batteries for general use (European Parliament, 2022). More importantly for this study, rechargeable batteries were shown to be available in different sizes by different battery suppliers, including the sizes of the disposable batteries that single-use SEDs were using. That opens the possibility of swapping them without risking changing the attributes associated with the battery size. Nonetheless, electronic devices, like those referenced at the beginning of this section, would first need to be rethought as non-single use.

4.1.3. Patch

As described before, the sleep device had a multilayered adhesive patch-base sensor. These assemblies are not rare to come along with small electronic devices, especially wearables used for monitoring.

The exploration inspected adhesive suppliers for medical assemblies to find environmentally friendly features in their catalogs. One supplier labeled some of the options as “Eco-friendly adhesive.” The *business development and innovation of the health care unit* (BDI) of the adhesive company in a meeting explained that the feature refers to solvent-free adhesives. This feature brings two avoided negative impacts; on the one hand, they reduce or eliminate volatile organic compounds (VOC), and with them, harmful emissions during the processing and service life of the adhesive are avoided (Sukanya, 2020). On the other hand, solventless adhesives decrease the need for fossil feedstock, bearing in mind that this is the raw material for solvents (BDI, personal communication, 2023). Another supplier offered “solventless” adhesives owing to the same characteristics. Adhesives for medical assemblies with superior eco-properties were rare to find. Some had percentages of “bio-based” fractions in their composition; however, they were not convenient for the assembly in question. The BDI added during the meeting that there is an increasing interest in developing solutions from biobased feedstocks, which would be a promising commercial alternative for the future.

This review of suppliers led to a research institution that recently developed a biodegradable cellulose nanocomposite substrate for recyclable flexible printed electronics. On the substrate, electronic components are mounted, and silver ink is printed; after three weeks, the substrate degrades on the soil and liberates the electronic components (Jaiswal et al., 2023). The multilayered assembly of the sleep device possesses silver ink-printed electrodes; thus, this case was relevant. Using this same substrate, the research institute introduced a biodegradable ECG patch that accomplishes degradation utilizing carbon ink (Behfar & Jaiswal, 2023). In line with the carbon ink, a company was found to provide recyclable printed electronics that can be disposed of as plastic waste rather than special waste, thanks to their use of plastic substrates and carbon inks. However, direct communication with the company was not possible.

The patch shows ready-to-use opportunities with solventless adhesives as they are available. More innovative solutions would have required collaborative efforts to adapt the solutions to the specific needs of the manufacturers. The research institute shows willingness to collaborate with the OEMs to implement its solutions. However, during the internship a preference for mature or ready-to-use solutions was noticeable on the manufacturers side; thus, options of this kind were not widely regarded.

During the previous supplier review, reworkable adhesives emerged as an interesting topic for the subsequent section 4.2 on design guidelines. Adhesive suppliers, offer tapes and liquid adhesive solutions for electronics labeled as “reworkable.” With this feature they pretend to offer a secure fixing of components and, with some solutions, advanced features as water and dust proofness while making the adhesive removable with no residue at the EoL to ease replacement, disposal of, and recycling of electronic parts (Tesa, 2022).

In summary, the PCBA shows a promising alternative, especially when the device is expected to be returned to the OEMs so they can put back in the loop the valuable components of the PCBA in remanufactured devices. Additionally, the technology is reportedly flexible enough to be implemented in different small electronic devices (SA, 2023). The only downside of a newborn market option is that since it is not widely spread it cannot be expected that EoL systems, as recyclers, would be able to take advantage of the technology, which, considering the challenges to efficiently recycle PCBAs, it is a great loss opportunity. Nonetheless, efforts to work jointly with local government and recyclers and this technology are developing (SA, 2023).

The presented batteries with superior eco-properties have limitations in their field of device application. For short-life disposable devices, they may present an excellent option when compared to current alternatives (e.g., Li-coin batteries). However, their shape factor could be a constraint, as explained before. Moreover, a substantial drawback is that rechargeable small electronic devices are out of the scope of these solutions as the batteries are non-rechargeable.

A common feature of these greener components is that they offer innately positive aspects to the SED's sustainability performance. For instance, solventless adhesives offer an inherently greener option in electronic devices, and so would be if bio-source adhesives started seeing a breakthrough, both due to their feedstocks. Similarly, as reported, the greener manufacturing process of the unzippable PCBA and the environmentally conscious batteries, with no hazardous materials, offer, from the beginning, a “positive net impact on the environment” (Cenci et al., 2022). It is important to note that the ability to take advantage of a device's superior eco-properties largely depends on the EoL choice made by the user. If users improperly dispose of SEDs or OEMs do not put in place proper return schemes, they will have limited opportunities to, for instance, reuse components from dismountable PCBAs; substrates may not degrade properly, and consequently, mounted components will go to waste.

Therefore, putting in place effective schemes to ensure adequate use of these features is crucial for maximizing their positive impact on the environment. Lastly, implementing good practices in a company can be challenging due to the need for collaborative efforts between manufacturers and suppliers, as it was shown that many of the options need to be customized to the needs of the manufacturer to meet technical specifications. This collaborative approach requires additional effort and willingness, often lacking in established routines that are facilitated by ready-to-use solutions, making it a complex but essential task for enhancing overall business sustainability.

4.2. Design guidelines

Table 2 displays the design guidelines from the assessment described in the methodology section. Appendix. A and Appendix. B shows a disclosure of the selection process. Table 3 shows key insights from the interviewees in relation the design guidelines. A discussion on the different categories follows.

Table 2. Design Guidelines

Category	**Design guideline**	**Additional remarks**	**Code**
Fasteners (FX)	▪ Use reversible fasteners	▪ Use metal screws, clicks. ▪ Avoid PSA, glue, and soldering.	F1
	▪ Promote the use of standard disassembly tools	▪ Standard: Regular screwdrivers (e.g., Philips), metal and plastic spattles, pliers, tweezers, etc. ▪ Special tools (must be avoided): screwdrivers with special-heads, heat gun, thermal pad, soldering iron.	F2
	▪ Minimize the type and number of joints	▪ Avoid different kinds of screw heads. ▪ Avoid opening mechanisms with a combination of, for instance, plastic clips, screws, and adhesive tape.	F3
	▪ Make disassembly joints quickly to identify and be accessible for the disassembly tool.	▪ Make screws axially accessible.	F4
Design architecture (AX)	▪ Apply modularity		A1
	▪ Reduce time and number of disassembly steps.		A2
	▪ Facilitate the identification, access, and removal of essential and critical components (non-recyclables, toxic, valuable, rare, etc.)	▪ Use reversible fasteners for fixing the battery, PCBA, and foreign materials (cardboard, foams, dust bags, etc.). ▪ Avoid enclosing materials permanently. For the PCBA: ▪ Clipped-on EMI shields are preferable rather than screwed or adhesive solutions. For the battery: ▪ Stretch and release adhesives. ▪ Mechanical spring-loaded slider. Simple connectors (no soldering).	A3

Continued

Continued

Material recycling (MX)	▪ Use recyclable materials	▪ Common thermoplastics: ABS, PP, PC, PC/ABS, HIPS, PE. ▪ Avoid polymer blends: POM/ABS, PA/ABS, composites, thermoplastic elastomers, and thermoset rubbers.	M1
	▪ Easy separability of incompatible materials	▪ Avoid molding different types of materials together (e.g., thermoplastic elastomer molded onto PP). ▪ Detachable solutions for foreign materials. ▪ Avoid fixing ferrous metals to non-ferrous ones.	M2
	▪ Promote mono-material design		M3
	▪ Avoidance of surface treatments		M4
	▪ Minimize hazardous materials		M5
	▪ Standardize plastic labeling in visible locations		M6
Others	▪ Provide End-of-Life information	▪ Manuals, descriptions, or videos showing the disassembly process.	O1
	▪ Use recycled materials		O2

Note: Adapted from Berwald et al., (2021); Bovea & Pérez-Belis, (2018); Martínez Leal et al., (2020); Schischke et al., (2013). See Appendix. A

Table 3. Design guidelines with remarks of different EoL handlers

Category	Code	Repairers	Manual Recycler	Automatic Recycler
Fasteners	F1	▪ Gaskets and rings in combination with screws and clips for water protection.	▪ Clips are superior to screws in recycling. ▪ Avoid heavy-duty adhesives	-
	F2	▪ Avoid special tools and parts that users may not have access to.	-	-
	F3	-	-	-
	F4	.-	-	-

Continued

Continued

Design architecture	A1	▪ Allow independent access to crucial components. ▪ Avoid permanently fusing or soldering between components.	-	-
	A2	▪ Use repairability scores to assess prototypes.	▪ Avoid time-consuming disassembles.	-
	A3	▪ Pay attention to the battery. ▪ Make enclosure easy to open.	▪ Make the enclosure easy to open.	▪ Avoid embedded batteries. ▪ Standardization of critical components position.
Material recycling	M1	-	-	▪ Avoid black-colored plastics. ▪ Use light-colored plastics. ▪ Avoid low-quality polymer.
	M2	-	-	▪ Prevent gluing together dissimilar materials.
	M3	-	-	-
	M4	-	-	-
	M5	-	-	-
	M6	-	▪ Label every piece of plastic.	-
Others	O1	-	-	-
	O2	-	-	▪ Incorporate recycled material into new electronics.

4.2.1. Fasteners

Within this category, four design guidelines are grouped. They rely on the principle of design for disassembly as they are related to their accessibility and ease of removal. F1 refers to the available fasteners that can be disassembled and easily removed. In the remarks, screws, and clips (e.g., snap-fit, press-fit, etc.) are commonly nonpermanent solutions suggested. However, their advantages may be jeopardized if guidelines F2, F3, and F4 are not considered. While screws are generally easy to unfasten, different kinds of screw heads hinder the disassembly process because it requires the distinction of the form factor and the selection of different sets of screwdrivers (Schischke et al., 2013). Additionally, tamperproof screw heads, like the Pentalobe introduced by Apple, which require a specific kind of screw drive to be opened, rule out the possibility to make screws reversible and accessible by anyone (The Repairers, 2023). Screw's location plays another crucial role; Schischke et al., (2013) described that "radially accessible" screws are challenging to remove, that is, having to place the tool in positions different from the axial position of the screw.

Clips, on the other hand, are problematic from a repairability point of view. Schischke et al., (2013) and two interviewees indicated that while disassembly clips tend to be easy, even using fingers or common tools as spatulas, they are likely to break, making the reassembly process knotty. The Manual Recycler highlighted that plastic clips may wear out and be more likely to break even with experienced hands. Nonetheless, the clips resistance is relative in every device; while Schischke et al., (2013) broke some clips during their disassembly tests in some of the tablets they studied, in other tablets, clips kept the device tightly closed and unbroken even after several trials of opening and closing.

From the recyclability point of view, Schischke and colleagues (2013) found through an interview with a recycler that a high number of screws are problematic. The recycler explained that they might use cruder processing methods to remove EMI shields with more than ten screws instead of unscrewing; even shredding them, if the battery has been removed, was mentioned as preferable. Moreover, the recycler said that a glued-in battery would be preferable to a screwed-on battery if a spatula can be easily placed under the battery for leverage.

Therefore, screws, for the most part, are the best for repairability as they do not pose a threat to the reassembly of the device; in contrast, from the recyclability point of view, screws can be unnecessarily more time-consuming than clips, especially when breaking a clip during the first steps of recycling does not compromise the rest of the process (Manual Recycler, 2023).

PSAs are advisable to avoid as they are considered a suboptimal fastening mechanism for disassembly (Berwald et al., 2021; Schischke et al., 2013); this is because they usually need special tools such as heat guns, heat pads, and solvents to weaken the bond (the latter is also required to remove residues) or even suction cups to force the adhesive to pull up (especially for devices with a screen such as phones and tablets).

The manual recycler did not point all PSA as problematic if the special tooling mentioned before is available and no heavy-duty PSA is used; however, he recognizes that special tooling brings an extra layer of complexity; for instance, the need for solvents to release the PSA also requires special protection, such as a hood in the recycling workshop.

Another disadvantage is that, from the repairability point of view, even when successfully removing the adhesives, specialized equipment, like jigs, are usually needed for the reassembly process; this is to ensure that the adhesive is applied with the correct pressure and for the right amount of time to achieve proper adhesion (The Repairers, 2023). The special equipment creates a barrier to entry, for instance, for “do it yourself” (DIY) repairs (The Repairers, 2023); nonetheless, this barrier to entry may be seen as an additional obstacle for companies pretending to implement remanufacturing practices in their business model. Reworkable tapes found during the supplier exploration do not seem to overcome the drawbacks of specialized tooling, but according to their description, one can expect that they will not pose as much of a challenge as, for instance, heavy-duty adhesives do.

The repairers' interview and Schischke and colleagues' work support manufacturers' reasons for using PSA, some of which can be extended to other non-green solutions.

- *Design aesthetics:* there is an increased market need for clean, sleek, and modern aesthetics in electronic devices. These features are achievable with PSA, which supports a small form factor, potentially saving overall weight compared to other bulkier methods such as screws (Schischke et al., 2013).
- *Extra protection:* consultancy in the mentioned internship proved wetproofing to be a concern in design choices to keep electronics inside the enclosure safe.

Waterproofing and dustproofing are among the features many kinds of PSA claim to have, as the supplier exploration proved. In contrast to that, the repairer interviewees brought up the fact that waterproofing tends to be hard to guarantee, especially when considering that once devices are out of their box, they are subject to environmental conditions that degrade the adhesive (Greenlee, 2023); instead, when there is water ingress, being able to access easily to the electronics is more important to be able to clean and repair the fault. To address both aspects, the interviewees suggested using screws or clips in combination with gaskets and rings, which proved efficient for protection while enabling easy disassembly. Nonetheless, they recognize it challenges the previous point related to bulkiness and aesthetics.

- *Manufacturing efficiency, costs, and electronic industry trends:* PSA may be faster to apply in an automated way in comparison to hand-assembled devices with screws and gaskets, which still require to be carefully fixed to get the correct torque and securement, which makes the former comparatively very inexpensive. In the highly competitive electronic industry, saving costs tends to be prioritized. In addition to that, there is a dominance of larger electronics companies in setting industry standards in manufacturing practices, like using PSA, that smaller manufacturers may follow because they trust the practices of well set-up factories.
- Liability concern: manufacturers may use a challenging-to-open fastening system to prevent customers from opening their devices and potentially causing harm to themselves and leading to legal issues.

Soldering is mentioned as another problematic fastening system since it is a non-reversible method and, in cases of repair, requires special tooling such as micro-soldering. However, this fastening system is more common in connections between components, for instance, batteries with soldered wires to the mainboard. Alternatives may be zero-insertion force (ZIF) connectors, which are easy to unclick. These connections are more critical from a repairability point of view because recyclers will generally cut the cables independently of the connector type (Schischke et al., 2013).

The interviews with the Automatic Recycler did not bring any additional insight into the set of guidelines regarding fasteners. The destructive nature of the disassembly process during the first step of recycling to manually remove the hazardous materials, which implements hammers or scissors, as mentioned by the interviewee, makes, overall, guidelines F2 and F4 not necessarily relevant. In this regard, there is no need for a meticulous separation of the different parts making up the device. Nonetheless, when removing the hazardous materials is too challenging in a moving lane, the devices go to a separate location in the plant where the extraction happens in stationary conditions; the interviewee mentioned that this is the case for all mobile phones. Although not explicitly stated by the interviewee, it can be argued that guidelines F1 and F3 should be considered for this scenario. This is because, regardless of the EoL handler's approach (e.g., a destructive one), adhering to these guidelines would make it considerably easier and faster to recover valuable materials.

When Guideline F3 is ignored, it proves problematic from the point of view of time and the complexity of disassembly. Schischke and colleagues found that the enclosure of a tablet consisting of a combination of three plastic clips and adhesive tape as well as two screws leads to scratches and the breaking of a plastic clip in the opening process, and thus that the opening process requires very delicate work to avoid damage. The small recycler gave the example of Apple earbuds, describing them as a very complicated small electronic device to tear down due to the excessive number of adhesives and glue; he explained that many recyclers would avoid this device due to the time-consuming task of successfully removing the battery of the charging case of a small gadget whose recycling value is not so striking. A teardown video by iFixit shows the necessity of an ultrasonic cutter to get through the plastic case since spattles and even a heat gun were not enough to pry the enclosure (iFixit, 2022, 1:42).

Although a reduced number of fasteners may make dismantling and repair uncomplicated, it's important to note that a higher number of fasteners and larger adhesives often results in increased overall robustness and resistance against mechanical stress (Schischke et al., 2013). Thus, designers should carefully consider this specific trade-off by conducting, for instance, drop-tests.

4.2.2. Device architecture

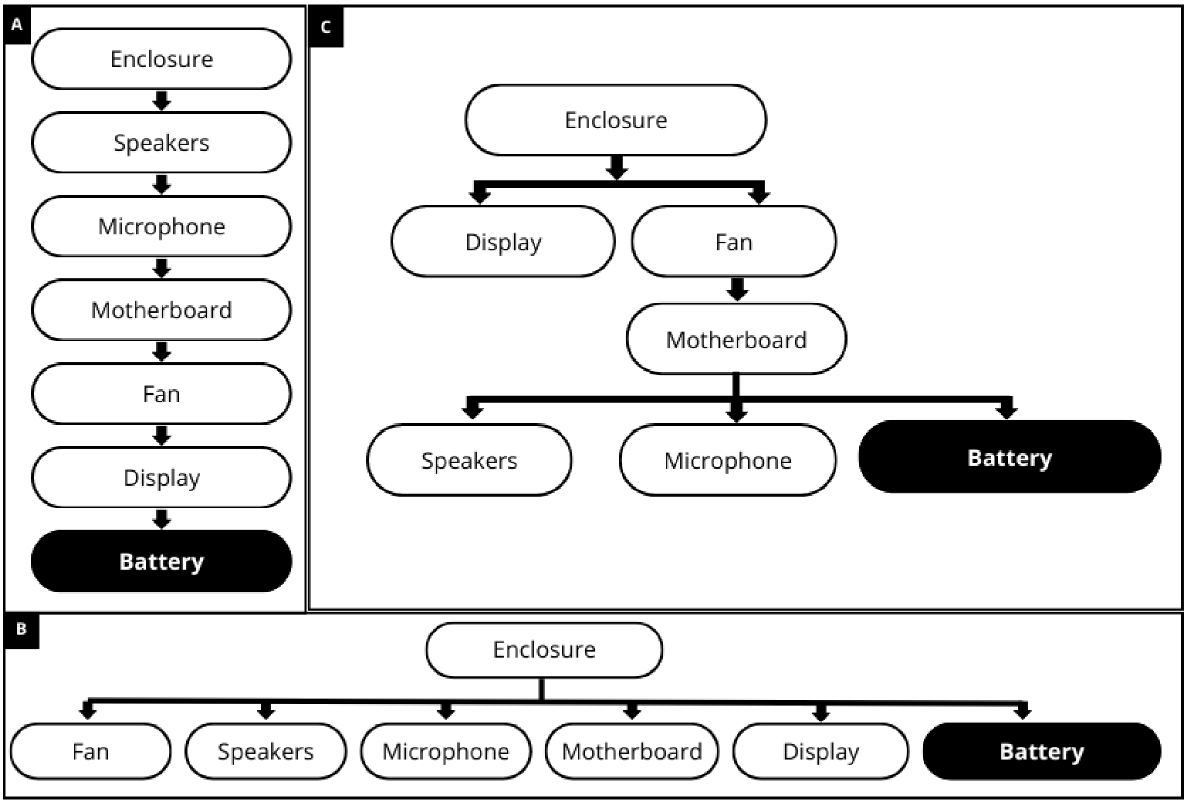
Device architecture contains design guidelines related to the distribution and accessibility of electronic components in the structure of the device. The literature review defined components requiring selective treatment; nonetheless, the interview with The Repairers extended this definition to the so-called "crucial components." From the lens of repairability, crucial components are those more likely to fail or need upgrades and whose role is critical for the device's functioning (The Repairers, 2023). Thus, they can change from one device to another. In smartphones, for instance, crucial components include the screen, which is prone to damage from drops, and the battery, which has a limited lifespan with a certain number of cycles. In other devices, gaskets and sealants could represent crucial components since they are predisposed to wear from physical stress. Designers can consider historical data to identify those components that are usually in need of repair within their devices (The Repairers, 2023). The Repairers stressed the need to select crucial components, so designers can pay more attention to their location, which should allow easy access for repairability or change.

During the interview with repairers, the definition of modularity (A1) was expanded to include the ability to "independently access" crucial components, which was not explicitly stated in the literature review. Its principle relies on the number of disassembly steps and the separation capability (The Repairers, 2023); thus, in A2 and A3 guidelines respectively. When assessing how independently accessible a component is, it is essential to consider how many steps or actions are required to reach that component (A2). The disassembly of a device can be subdivided into disassembly tasks, e.g., disconnecting, removing adhesive, cleaning, exchanging tools, etc. (Talens Peiró et al., 2017). According to Schischke and colleagues, the number of disassembly steps—an operation that finishes with the removal of a part or the change of a tool—indicates the complexity of the disassembly and influences the dismantling time, which is prime when considering commercial repair or recycling (Schischke et al., 2013). The disassembly time is highly dependent on the fastening selection, which has already been discussed in the previous section.

The Repairers use a disassembly tree to illustrate the accessibility of components at different stages. Figure 2A represents a disassembly tree with a linear sequence; as it was brought already in the literature review, getting to a specific component in an electronic device may require removing before other elements. Disassembling this architecture involves a higher number of steps, which increases the risk of damaging other components during the process. This can make it challenging to identify the location of a failure committed during the disassembly process once the device is reassembled (The Repairers, 2023). Thus, a "shallow" disassembly (Figure 2B) sequence with independent access to major components is the most desirable from a point of view of disassembly. However, a more realistic view, where manufacturers prioritize aspects additional to disassembly (Suovanen, 2023) makes disassembly trees look like Figure 2C.

The Repairers brought up the topic of “repairability scores.” This method attempts to quantify the complexity of repairing or recycling an electronic device. There are different indexes, like the self-attested French Repairability Index or the iFixit repairability score. The latter was discussed during the interview, and it goes from zero—disassembly is destructive or impossible—to ten—best in class—with an intermediate score of five marking the line between “need for professional repair” and “fixable by yourself” (Suovanen, 2023). While the repairability score considers 10 % of the availability of the service manual and another 10 % of the availability of replacement parts, the majority (80 %) focuses on the design.

Figure 2 Disassembly trees



Note: A. Linear disassembly tree; B. shallow disassembly tree; C. More realistic disassembly tree. Adapted from *How iFixit scores Repairability* by Suovanen (2023)

The design is assessed assigning weights to critical components based on their importance for repair. The process includes creating a disassembly tree, mapping repair paths, and converting actions and tools into numerical values. Time-based calculations are made using preassigned time intervals (proxy times) for common actions, ensuring consistency across devices (Suovanen, 2023). Tools used are scaled based on factors like cost, availability, skill level, and safety risks. Penalties are applied for proprietary (e.g., Pentalobe screwdriver) tools and tool changes (Suovanen, 2023). The entire repair path, including reassembly, is traced, considering the time and tools needed. The final repairability score is calculated by summing the products of proxy times, tool scaling factors, and component weights (Suovanen, 2023).

“Recycling scores” were also a topic of conversation with the small recycler, which follows a similar logic when assessing the design architecture of the device. The differences are the lack of consideration of the reassembly step and the assumption of different recycling scenarios being (1) shredding preparation, where the focus is pulling out the battery and hazardous materials; there is no need for careful disassembly; (2) tear down, which consists in separating the different parts of the device; there is no need for careful disassembly either – and (3) full-parts harvesting, where the aim is to save components, like mother boards, for reuse; the nature of this disassembly is more gentle. Additionally, the recycling scores considers material selection, but the following section 4.2.3 will discuss that matter.

In relation to A3, the separation capability of a component without causing damage is another key aspect of independent access. This is the case for some critical components, like the random-access memory (RAM) or ports being soldered onto the main board, which then results in costly reparations since it might be necessary to change the whole board instead of replacing a single component (The Repairers, 2023). In guideline A3, the battery received a lot of attention on the side of the three interviewees, with an emphasis on the risks associated with wrongly manipulating this component during recycling or repair, which may result, as explained in the literature review, in fire generation due to an unintended puncture. Embedded batteries in the device were highly discouraged by the Automatic Recycler, who stressed that battery explosions are one of the most common and riskiest situations in WEEE recycling plants. During that interview, the ideal scenario of having batteries in a standard position was discussed, since the identification process is currently supported by the operator’s experience.

In Schischke and colleagues’ assessment of tablets, disassembly discusses battery pack accessibility. They identified two design options and two special cases. The first design option uses a battery housing of plastic or metal, similar to a tray, which keeps the battery in place with screws. The second design uses glue directly in the form of adhesive strips. Schischke et al., emphasized the novelty of one of the tablets using "pull tabs" for adhesive tapes that help to remove the battery without requiring extra tools once the battery is accessible. This adhesive technology is called “stretch and release,” and it is part of the portfolio of reworkable tapes from tape suppliers explored in section 4.1.3. The iPhone 13 teardown shows that this smartphone uses this fixation method; however, when pulling the adhesive, it is prompted to break and thus needs to use solvents anyway (iFixit, 2022a, 4:25). Similarly, a teardown of the iPhone 15 Pro Max uses the second type of design described before, where isopropyl alcohol was needed to lose the adhesives even though "pull tabs" to ease the removal of the adhesives were provided (iFixit, 2023, 1:04). Interesting in this video, is the need to remove several parts before finally getting to the pull-tabs.

Lastly, one of the devices studied by Schischke et al. had a mechanical spring-loaded slider function as the locking mechanism securing the battery in the device. The advantage of this system was the one-step and no-tool disassembly. Similarly, some small smartphone manufacturers (e.g., Teracube, Purism Librem, and Fairphone) have accomplished designs that allow securing the battery without gluing it and allowing access to the battery in two steps and with no tools; this is possible using indents in the back panels (notches) giving space to fingernails to pry up the enclosure and have direct access to the battery which can be removed pulling up with the fingers (iFixit, 2021, 0:22). One of the tradeoffs of non-embedded batteries is related to aesthetics; non-embedded batteries lead to bulkier designs compared to sleeker embedded battery designs (iFixit, 2021, 3:29).

The simple notch system to open the enclosure is seen as an advantageous design choice for whoever is handling the EoL of the device (Schischke et al., 2013). Opening the enclosure is a key part of the disassembly process because it gives access to the rest of the components inside (The Repairers, 2023). Nonetheless, the easiness of opening the enclosure is strictly connected to the guidelines in the section 4.2.1 above.

Guidelines regarding device architecture have special importance when considering design for recycling. Recyclers must strike a balance between the effort and time spent on disassembly and the potential value of recovered components. This calculation influences their decision to either disassemble devices gently for component harvesting or resort to more aggressive methods like shredding (Repairers, 2023). Overall, when the disassembly process is too challenging, recyclers will not spend too much time trying to tear down the device into its different parts. The manual recycler mentioned that for time-consuming dismantling devices, they would require extra economic incentives previously agreed upon. It was also added that there is a chance for some components and parts that are too challenging to liberate to end up in the so-called “mix plastic bin,” which goes to a different recycler that will try to harvest whatever is possible or ultimately get rid of it by means of energy recovery.

A similar scenario occurs with the Automatic Recycler regarding PCBAs, which recognizes the ideality of removing all PCBAs during the preparation before shredding from the point of view of recycling efficiency, that is, recovering more materials from the PCBAs when undergoing their individual recycling process. Nonetheless, the decision-making process is closely related to the time constraint; if the PCBA is too challenging to remove manually, it will continue its way to the shredder since a manual process is not profitable with high volumes of WEEE (Automatic Recycler, 2023); thus, the recycling of the PCBA will indirectly occur with the rest of the materials that are shredded.

4.2.3. Material recycling

Six guidelines were grouped within this category and are all related to the design for recycling that focuses on easing the recycling process. Thus, material selection has an essential role in this category. Polymers receive particular attention within the remarks found in the literature due to the challenge of sorting the WEEE plastic mixes during the recycling process (Berwald et al., 2021; Manual Recycler, 2023).

Additionally, as reported in the literature review, polymers usually account for a large fraction accounting for the enclosure and other structural and protective components.

M1 encourages the use of “recyclable materials.” Thus, it refers to those materials whose recycling processes and technologies are widely spread and known in WEEE recycling facilities; that is the case for ABS (one of the most common plastics in small electronic devices), PP, PA, PC, HIPS or PC/ABS. Regarding the latter, while design guidelines do not recommend polymer blends, existing technologies properly recycle PC/ABS (Berwald et al., 2021).

After the interviews, it became clear that recyclable also meant “recognizable”. On the side of the automatic recycler, one part of the automatic sorting happens with optical sorting machines. Low-quality polymers may be challenging to identify as "coded polymers” (Automatic Recycler, 2023); for example, fiber plastics (a composite) are not recognized as coded polymers, and they are ruled out of the process and sent to energy recovery. Thermosets are another material sent for energy recovery, while rubber is possible to separate from the plastic streams using vibration and later be recycled (Automatic Recycler, 2023).

During the preliminary step before shredding, various “foreign materials” such as cardboard, wood, and textiles are removed, stressing the need for detachable solutions (M2). The Automatic Recycler mentioned, albeit with a degree of uncertainty, that components like the multilayered assembly of the sleep device would be discarded at this stage and subsequently incinerated. The challenge of recycling this kind of component had already been anticipated during the internship, on the one hand, for the assembly complexity and the small amount of materials. On the other hand, concerns arise in relation to the human skin contact of the patch. Nonetheless, for the latter, the Automatic Recycler mentioned that would not be a concern since, due to the large volumes they process, the patch would pass unnoticeably. The interviews with recyclers and the BIC on adhesives indicated that the best approach for this assembly would involve collaborating with a recycler who is willing to explore the potential recycling of certain materials within it.

Schischke et al., (2013) reported that recyclers consider black-colored plastic to be plastic with low value. However, they and design guidelines do not elaborate on the reasoning behind this. Nevertheless, the automatic recycler shed light on this matter. It explains that dark-colored plastics are problematic because they cannot be recognized by optical sorting machines, which are a very efficient technology for light-colored pieces of plastic. The reason for the limitation is that black targets have very low reflectance in the NIR spectral region; hence, the signal-to-noise ratio of the current NIR sensors is too low for classifying black polymers (Rozenstein et al., 2017). Due to this technical constraint, the automatic recycler chose to sort the plastics by density difference and then, further refine the fractions with electrostatic systems. During the first step, all black plastic sinking is assumed to contain hazardous flame retardants, which, as explained in section 2.5.4, recyclers are obliged to get rid of; lastly, it is incinerated because there is no additional and economically viable way to sort black plastic (Automatic Recycler, 2023 & Feenstra et al., 2021). Hence, this process has losses of dark plastic that could be recovered, but it is instead deemed hazardous. During the interview, it was estimated that approximately one-third of the plastic input to the facility is incinerated as hazardous flame retardant and unrecognized plastic. Thus, on the side of designers, they could select lighter colors which could be efficiently sorted by optical sensory machines.

A significant difference between the automatic recycler and the manual recycler is in relation to guideline M6. For the latter, plastic labeling is very necessary, as it is the only reference available to sort the plastics. Dimitrakakis et al., (2009), who inspected 180 kg of WEEE, found that only 6.8 % of the plastics bore a molding mark indicating the type of polymer. The manual recycler explains that they partner up with some OEMs, and in that case, they will make sure to mark the plastics to ease their job. Additionally said that plastic pieces with no visible marks end up in the mixed plastic bin, where a different recycler may attempt to extract materials using other methods (Manual Recycler, 2023). On the other hand, the Automatic recycler commented that labeling would be impractical for them since automatic sorting takes care of the identification process.

In relation to guidelines M2 and M3, the Automatic Recycler pointed out problems associated with gluing two different kinds of plastics together, which is usually done for aesthetic purposes (Automatic Recycler, 2023). During the shredding process, the result is a small flake of two dissimilar materials, which will most likely be unrecognizable by the sensory machines sorting it wrongly (Automatic Recycler, 2023). In addition to gluing different plastics, this problem could arise with multiple K processes, that is, the injection of different plastics into the same mold (Berwald et al., 2021). In some design guidelines coatings (M4) are considered problematic because they could reduce value of plastic fractions (Schischke et al., 2013) or change the density of plastics, which can cause the plastic to end up in the wrong material stream (Berwald et al., 2021) the Automatic Recycler did not see them as a relevant concern even though recognizes that in rare cases a wrong sorting may occur.

Between the plastic fraction and the ferrous and non-ferrous fraction, plastics were confirmed to be more challenging. Berwald et al., (2021) also elaborated on the metal fraction, suggesting the principles contained in M2 and M3; for the Automatic Recycler, it did not seem as problematic as it is for plastics, arguing that the smelting process of metal recycling is less delicate and adaptable afterward. However, it still recognizes that high-purity streams are desirable for these materials.

No outputs from the interviews could be related to guideline M5. As mentioned in the previous section, interviewees stressed the importance of making hazardous materials, like the battery, accessible; however, there was no direct comment in relation to reducing the number of hazardous materials. This could be explained with the regulations already in place ruling this matter (e.g., the RoHS Directive). Nevertheless, and relatable to M3, both recyclers stress that devices consisting of fewer materials are easier, cheaper, and more efficient to recycle.

4.2.4. Other guidelines

O1 and O2 were grouped in this category because they did not fit into any of the other three major categories. O1 has significant relevance in a repair scenario. As was described before, 10 % of the repair score given by iFixit depends on the availability of manuals to disassemble the device. Mars et al., (2016) found that the lack of information to enable better repair of EEE is one of the major barriers today to more device reuse and refurbishment. Schischke et al., (2013) observed that when specific design information is not available, a repairer or refurbisher could cause unnecessary damage, which degrades the product’s value; efforts at depolluting could be ineffective; and recyclers could spend unnecessary time accessing critical components, increasing cost.

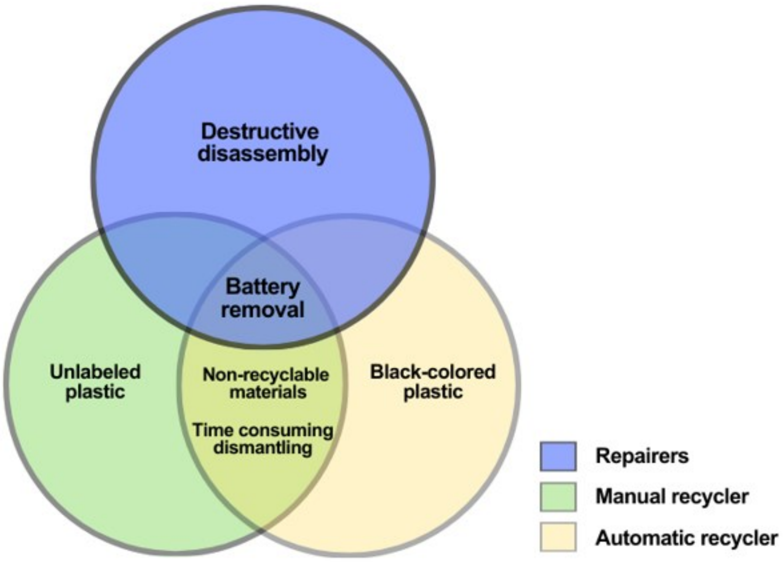
O1 was challenged by the Automatic Recycler, considering that the volumes and variety of devices treated by them would make the task of using a manual very inefficient. However, in an ideal scenario, it was discussed during the interview that labeling the device and indicating where the battery is would be advantageous. Additionally, in the case of a manual recycler, one can anticipate that a handbook could be helpful, especially when batches of the same device are treated; the recycler interviewed by Schischke, and colleagues added that knowing the opening mechanisms in advance would be helpful. On the side of manufacturers, however, they may not feel comfortable publishing such information for potential liability if someone gets injured during the repair process (Mars et al., 2016), a similar logic behind making devices hard to repair and discussed before.

O2 enters the framework of design from recycling. Some argue that this framework is crucial to achieving complete circularity (Martínez Leal et al., 2020); “otherwise, we [recyclers] produce plastic for nobody” (Automatic Recycler, 2023). Post-consumer recycled plastic (PCRP) faces the challenge of having a different visual effect to virgin plastic; it is, for instance, not so bright or shiny and is more opaque (Automatic Recycler, 2023). Thus, efforts on PCRP focus on accomplishing the aesthetic features of virgin materials (Feenstra et al., 2021) or encouraging designers to implement PCRP as they are so users get used to the new aesthetics (Automatic Recycler, 2023).

4.2.5. Challenges for SED EoL handlers

The preceding results and discussions revealed different challenges faced by each EoL handler. Figure 3 illustrates these challenges, showing the interconnections between the handlers. These challenges encompass aspects that could impede, endanger, or entirely hinder the execution of EoL tasks effectively. Table 4. presents guidelines discussed to address these challenges.

Figure 3. Challenges faced by EoL handlers.



Repairers pay special attention to “non-destructive” disassembly to make the reassembly process possible. Thus, FX and AX are the most relevant for this case. Not all the suggestions in F1 are optimal for repairers since some of them, like clips, are prompt to break. F1 directly influences electronic aesthetics, and while some PSAs prove to be feasible to unfasten, they are suboptimal from the lens of repairability, especially when better practices are available. F4, in particular the accessibility aspect, is relevant to avoid mistreatment of the areas surrounding the fasteners. F2 is particularly problematic for DIY repair, but experienced repairers most likely count on adequate tools; however, this should not be considered a justification to overlook F1. F3, in particular the aspect about the number of joints, has a close relationship with time consumption, which does not seem to be as problematic for repairers as it is for other EoL handlers. Nonetheless, different types of joints could potentially make the disassembly process sloppier.

Guidelines pertaining to AX are paramount in preventing destructive disassembly. These guidelines lack specific remarks or exceptions that might compromise a repairer's task while favoring other EoL handlers, like it was the case for screws and clips. Meticulous consideration of A2 and A3 would ensure independent access to vital components. Moreover, evaluating the device right from the prototyping phase, using repairability scores, can provide valuable insights into areas of the device requiring improvement. Lastly, while having spare parts may appear tangential to the central theme, it should not be dismissed, as it is fundamental for repair as well (The Repairers, 2023).

Table 4. EoL Handler's challenges and design guidelines

EoL Handler	Challenges	Guidelines	Additional remarks
Repairers	Prevent destructive disassembly.	FX and AX	F1 should involve the use of fasteners that are not prone to breaking.
Recyclers	Prevent futile feedstock.	M1, M2, M3, M4 and M6	Black-colored plastic is very problematic for automatic sorting while M6 is not relevant when automatic sorting is in place.
	Prevent time consuming dismantling.	FX, AX and O2	In F1 fasteners prompt to break are not problematic and could be advantageous. O2 serves as an incentive for recycling operations.
Repairers and recyclers	Safe removal of the battery	A3 in synergy with A1, A2 and FX	Easy enclosure removal and selection considering F1 are uppermost.
	Efficiency	O1	It could be valuable in any case according to the format.

Extending the repairer's classification to a company with a remanufacturing scheme is relevant due to shared concerns about disassembly challenges and repairability. The insights gained from repairers' perspectives can inform strategies for efficient disassembly and reassembly, benefiting both individual repairers and larger-scale remanufacturing operations in OEMs.

In both recyclers' cases, disregarding M1, M2, and M3 can jeopardize the recycling process due to futile feedstock; for the automatic recycler, avoiding black-colored plastic is paramount for more efficient recycling. While M4 may be considered relative to the recycler's technologies, the risk of hindering the process and the adherence to the mono-material principle described in guideline M3 suggests avoiding surface treatments. Guideline M6 pertains to the recycler's identification process, making it seemingly irrelevant for recyclers with automatic sorting systems. However, neglecting this guideline could compromise the efficiency of others dependent on this identification process. While the importance of M5 is evident —handling two batteries instead of one pose higher risk — its relevance as a guideline for designers might appear diminished due to stringent regulations addressing this issue already.

However, the literature review revealed that certain hazardous materials might fall outside these regulations' scope, a concern more pertinent to the earlier-discussed section (4.1) on component selection. Consequently, the guidelines from AX, especially A3, which facilitates the easy removal of components, prove more crucial than M5.

Time is a crucial factor for recyclers concerning their economic benefit and could significantly impact proper and efficient recycling. FX guidelines, in synergy with AX, are vital for improving dismantling times; thus, F1 and F3 are pivotal. F1 may involve fasteners prone to destruction, like clips, and F3 could impede efficient disassembly even in cases of destructive opening or hinder component harvesting operations. Considering the various challenges outlined in the literature review that threaten the economic viability of the recycling process, any measure simplifying recycler operations is essential to support this EoL. O2 can be viewed as an incentive for the recycling industry and a significant step towards closing the loop.

A3 emerges as one of the most crucial guidelines, regardless of the EoL scenario. One commonality in the interviews among all three types of EoL handlers lies in the need to safely remove the battery. Paying close attention to the guidelines from FX and the others from AX, along with the shallow design and individual access principles, is vital, as they synergize with A3 to formulate the most effective strategy for battery accessibility. A notable point from A3 underscores the importance of enclosure removal, a consideration applicable in all three cases. Therefore, designers should explore F1 options that facilitate this process, including design features such as notches.

While O1 may not be a fundamental guideline, its applicability proves valuable at any stage of the EoL process. The specific delivery of information can be tailored to each scenario for optimal efficiency; for instance, providing manuals for repairers and incorporating marks on the device for recyclers would enhance usability and effectiveness.

4.3. Considerations for designers towards greener small electronic devices and sustainability

It is crucial to emphasize the significance of manufacturers understanding the EoL implications of their products beforehand. This knowledge enables them to focus their efforts on a specific set of considerations during the design phase. For instance, in a hypothetical scenario where a return scheme is implemented for the sleep device — allowing patients to send the device back to the company after their study — manufacturers can leverage the repair-oriented guidelines to facilitate the disassembly process. This approach would enable them to harvest and reuse various components of the returned device in remanufacturing strategies. Non-destructive disassembly techniques become pivotal here, enabling the recovery of valuable parts such as the PCBA and even the enclosure. In this scenario, manufacturers must carefully select components conducive to a remanufacturing scheme, such as “easy to repair” unzippable PCBAs and rechargeable batteries with extended lifespans.

On the flip side, as evidenced by this exploration, single-use electronic devices should, at the very least, be designed with simplicity in mind for their EoL phase. The interviews shed light on the fact that small electronic devices lack significant value for recyclers, mainly due to their minor size, making material extraction financially unattractive (Mars et al., 2016). Thus, effortless recycling becomes a vital aspect in encouraging recyclers to engage with these devices. Additionally, manufacturers must be discerning in selecting components that not only meet technical requirements but also offer environmental advantages. For instance, in a single-use scenario, they should aim for a power supply similar to the ones encountered in this exploration, representing the forefront of eco-friendly innovation in this specific battery application.

While it appears advantageous for designers to concentrate on a specific “Design for X” framework (i.e., aligning their efforts with a predetermined EoL scenario), the insights gleaned from the literature review suggest that disregarding guidelines from different X frameworks could be shortsighted. Islam et al. (2021) highlighted the multitude of circular paths that small electronic devices might follow at the discretion of users, whether they undergo repair, sharing, storage at home for years, or eventual recycling. This variability underscores the importance of always considering guidelines addressing recycling, even when the intended pathway is different. In this way, no matter the circular EoL, devices will be adapted for it.

Nevertheless, in a highly probable scenario, the EoL trajectories of small electronic devices may deviate from circular paths, posing a challenge that arguably falls beyond the purview of designers and the scope of this research on sustainable practices. As suggested by the literature (Dimitrakakis et al., 2009; Forti et al., 2020), the improper sorting of many small electronic devices, leading them to end up in the incorrect bins, raises significant limitations not only for designers but also for the entire field of green electronics. Despite emerging innovations in degradable components, including batteries, and materials with superior eco-properties, these solutions are not yet fully developed, and they give no sign of being “bin-suitable” signifying that proper EoL processes will still be necessary.

While the correlation between facilitating EoL pathways and users' preferences for these pathways deserves further exploration, one could argue that, for instance, the establishment of features easing repairs might address some challenges hindering users from repairing and refurbishing devices. These challenges often involve high costs due to the underdeveloped repair industry (Islam et al., 2021); supporting this industry from design may indirectly address these hurdles and encourage users to embrace more circular pathways. This observation points in a promising direction for future investigations in the realm of sustainable electronics.

The success of designing a green electronic device is intricately tied to the manufacturers' ability to identify suppliers who offer not only eco-friendly solutions but also components that are technically adaptable. This challenge is particularly daunting in an industry still in its nascent stages, as the supplier exploration proved, with most innovations possessing a relatively low level of maturity. Overcoming this hurdle demands heightened efforts and commitments from manufacturers to, for instance, strategically partnership to materialize solutions that go a step forward in the sustainability scale or assume trade-offs that benefit, for example, sustainability over aesthetics. Moreover, the challenge extends to the EoL phase. OEMs willing to treat all their components optimally must assume a more active role in the EoL. This proactive involvement could manifest through collaborations with recyclers, enabling the salvaging of valuable parts that might otherwise end up mismanaged, such as the patch in the sleep device. Additionally, incentivizing recycling processes that may not be profitable for recyclers can further enhance the circularity of SEDs, reinforcing the manufacturer's commitment to sustainable practices.

The broad and often vague concept of sustainability makes defining the best practice in designing small electronic devices challenging. However, the literature review on the concept of sustainability and green electronics highlighted the interconnection along the product lifecycle that presents an opportunity to enhance overall sustainable performance by addressing specific phases. Moreover, this same reasoning seems to apply in the interconnection between the three dimensions which compound sustainability. That could justify the exhaustive focus on the environmental dimension when the literature refers to “sustainable electronics.” Additionally, the issue of WEEE proves to be highly connected to the detrimental state of the environment, which, in turn, affects other dimensions, such as the social aspect. Hence, it is accurate to focus efforts on electronic equipment that attempt “directly or indirectly have a net positive impact on the environment compared to their alternatives” (Ceci et al., 2022, p.26).

In this context, designers do not necessitate complex solutions to start making their devices more sustainable. Adopting readily available practices such as, ensuring battery accessibility, choosing recyclable materials, or opting for solventless adhesives may not be groundbreaking but they swiftly yield a net positive impact. Thus, while transitioning to more refined strategies in collaboration with other supply chain stakeholders, these initial measures contribute significantly to the sustainable journey of electronic devices.

Chapter 5. Conclusions and perspectives

This exploration has delineated two distinct approaches for fostering sustainable practices in SEDs. The first approach centers around the notion of superior eco-properties, supported by an emerging but extensive research area depicted in the literature review. This area explores novel materials to address challenges related to resource depletion, hazardous material usage, and intricate EoL processing associated with electronic devices. This research has identified mature solutions from suppliers in line with this concept. Despite the limited number of alternatives, these options boast significant environmental significance.

One available option involves an innovative unzipping technology to reuse components from PCBAs. This groundbreaking approach not only addresses the issue of component reusability but also significantly reduces the overall CO_2 footprint during its manufacturing process, outperforming conventional PCBAs in terms of environmental impact. Upcoming commercial advancements in disposable batteries focus on reducing hazardous materials within the component. A noteworthy development presents biodegradability as a promising EoL disposal route for batteries. Additionally, biodegradable substrates for printed electronics and assemblies for monitoring devices are transitioning from prototype stages to becoming viable solutions for manufacturing companies.

However, the limited availability of suitable options creates a highly inflexible design landscape. Among these options, batteries have proved particularly challenging to adapt due to their shape factors, which influence several other design aspects. This challenge underscores the difficulty of finding universally applicable solutions. Moreover, many of these innovations are not readily available for purchase; instead, they often demand extensive collaboration with suppliers to adapt them to the requirements of SEDs.

Interviews for the second approach on design guidelines, which aims to connect designers with the EoL scenarios for SEDs, shed light on the most pressing challenges that EoL handlers face. Battery extraction emerged as the paramount concern among all the EoL handlers. Destructive disassembly methods represent a threat to remanufacturing and repair paths, and time-consuming teardown processes and non-recyclable materials in devices could compromise recyclers' profits and hinder the most efficient recycling paths for components in WEEE.

When analyzing the selected fifteen design guidelines against the challenges, those emphasizing fasteners—specifically, their reversibility, identification, number, and accessibility—in conjunction with those focusing on design architecture, encapsulated by the concept of independent access to crucial components, directly addressed the challenges related to safe battery removal, time-consuming disassembly during recycling, and non-destructive disassembly. Furthermore, guidelines addressing the material recycling feedstock proved crucial to the efficiency of the recycling process. However, some guidelines showed to be complementary rather than essential. Incorporating recycled materials not only resulted in a way to close the loop but also as an incentive for the recycling industry. Providing design information could make the repairing process more efficient. Lastly, assessing designs with repairability scores may give hints to designers on what is needed to improve.

Notably, not all reversible fasteners were suitable for remanufacturing, and labeling plastic parts might be vital for certain recyclers, while to others, it remains useless. Moreover, design guidelines addressing recycling remained pertinent even when recycling was not the predetermined EoL scenario, acting as a precautionary measure. These considerations led to the recommendation that designers explore the nuances of design guidelines and EoL scenarios.

It is essential to consider these approaches collectively, as they present both opportunities and challenges. The first approach, focusing on "superior eco-properties," reveals promising innovations in the literature, although many of these solutions are not yet readily available on the market. Thus, design guidelines may account for the negative impact by making the EoL management of conventional-non-ecofriendly components less problematic while more innovative products are available. Additionally, while this work labeled greener components as “inherently positive,” it also stressed that improper EoL handling might render its eco-properties wasted, something that the design for EoL could help to prevent. On the other hand, the design guidelines, while crucial for the EoL, often conflict with other design priorities such as aesthetics, liabilities, and costs. Suppliers may play a key role in solving this conflict of interest by offering solutions like the stretch and release PSA, demonstrating that sustainable practices and other design priorities could coexist harmoniously.

The core objective of this research was to equip designers with practical tools for creating more sustainable SEDs. Using the metric that the definition of green electronics provides, referring to equipment that has a net positive impact on the environment compared to their alternatives (Cenci et al., 2022) and its interconnection to the sustainability concept, one can argue that the solutions derived from this exploration would result in avoided impacts associated with greener SEDs. Thus, they serve as valuable resources for designers striving to make their creations more sustainable.

However, it is also essential to acknowledge the limitations of this research. The exploration of suppliers, conducted within the context of a specific medical monitoring device, might have overlooked solutions applicable to other SEDs. Therefore, a broader scope in this regard is recommendable for upcoming research. Additionally, while this research presents guidelines as ready-to-use solutions, it also recognizes that for many of them, their adaptation in the manufacturing phase may not be straightforward. Hence, this work suggests other research to explore more thoroughly the practical application of these guidelines. Lastly, as qualitative research, this study paves the way for quantitative inquiries, aiming to measure the avoided impacts that these recommendations offer to designers.

This work addresses a prevalent knowledge gap among designers and manufacturers regarding sustainability in SEDs. Achieving sustainability in EEE is inherently complex due to the intricate material compositions necessary to achieve adequate performance and meet customer expectations. Moreover, as these devices pervade essential sectors like digitalization, the challenge intensifies. The demand for these devices is rapidly growing, while sustainable solutions often progress slower and remain less known. Despite these challenges, this research contributes vital practical insights to the circular realm. It advocates that, in the interim, incorporating minor adjustments aligned with the key recommendations provided herein can significantly enhance the device's sustainability performance.

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Appendixes

Appendix. A Design guidelines selection

Guidelines mentioned by both authors were selected. Additionally, three design guidelines from a single author were chosen based on their assumed relevance for SEDs.

Table 5. (Appendix A). Selection of design guidelines

Bovea & Pérez-Belis (2018)	Martínez Leal et al. (2020)	Resulting design guideline
▪ Use joints than can be disassembled rather than fixed joints	▪ Fasteners must be easily removed	Use reversible fasteners.
▪ Use standardized joints. ▪ Use screws with the same metrics.	▪ Promote the use of standard disassembly tools. ▪ Minimize the required number of fastener disassembly tools.	Promote the use of standard disassembly tools.
▪ Minimize type of joints ▪ Minimize the number of joints	▪ Minimize the number of different types of fasteners. ▪ Minimize the number of fasteners.	Minimize the type and number of joints.
▪ Be able to quickly identify disassembly joints. ▪ Use easily accessible joints.	▪ Fasteners must be easily identified. ▪ Fasteners must be easily accessible (including the space for the disassembly tool).	Make disassembly joints quickly identifiable and accessible also for the disassembly tool.
▪ Adopt modular design.	▪ Make the product as modular as possible.	Apply modularity.
▪ Facilitate the accessibility of essential components (for potential reuse/recycling)	▪ Components containing non-recyclable, non-compatible, toxic, valuable, rare, and critical materials must be easily identified/ accessible/ removed/ separable	Facilitate the identifiability, accessibility, and removability of essential and critical components: non-recyclable, toxic, valuable, rare, etc.

Continued

▪ Use materials compatible for recycling.	▪ Use recyclable materials. ▪ Choose materials that can easily recover their original properties after recycling.	Use recyclable materials.
▪ Unify materials in the components joined by fixed joints.	▪ Where the materials of inseparable parts or sub-assemblies are not compatible, ensure that they are easily separable. ▪ Avoid the mixing of materials in assemblies. ▪ Use fasteners made of a material compatible with the other parts. ▪ Use compatible materials (that can be recycled together) in the product or sub-assembly.	Easy separability of incompatible materials.
▪ Promote mono-material designs.	▪ Minimize the number of different types of material. ▪ Mono-material strategy: favor using a single material per product or sub-assembly. ▪ Avoid the mixing of materials in assemblies. ▪ Use fasteners made of a material compatible with the other parts.	Promote mono-materials
▪ Avoid using surface treatments	-	Avoidance of surface treatment.
▪ Minimize using hazardous materials	▪ Avoid or reduce the use of substances, materials, or components harmful to humans or the environment	Minimize using hazardous materials.

Continued

Continued

▪ Label Materials	▪ Standardized coding and marking of materials to facilitate their identification (especially plastic parts). ▪ Place identification elements in visible locations ▪ Standardized labelling of products and components on recyclability, incompatibility, and/or toxicity so that they can be easily identified from recyclables and waste streams. ▪ Place identification elements in visible locations.	Standardized plastic labeling in visible locations.
-	▪ Provide useful processing-related information.	Provide EoL information.
-	▪ Use recycled materials.	Use recycled materials

Appendix. B Discarded guidelines

Guidelines specific to a single author were excluded. When referenced by both authors, their exclusion is justified.

Table 6. (Appendix B). Discarded design guidelines.

Author	Design Guideline
Bovea & Pérez-Belis (2018)	Extension of life span
	Timeless design
	Adaptability
	Upgrading
	Size components to make their handling easier
	Design to avoid dirt accumulation
	Use materials that overcome cleaning processes
	Minimize the use of parts that require frequent repair/replacement
	Use components with similar life span
	Incorporate systems to monitor falling components
	Use standardizes components
	Minimize variations in the appliance
	Use materials with a low environmental impact (recyclable, low energy content, etc.)
Martínez Leal et al. (2020)	Increase the linearity of the disassembly sequence.
	Increase the linearity of the disassembly sequence.
	Minimize divergence in the dismantling sequence order.
	Homogenize the principles of assembly and disassembly.
	Design the product so that it can be easily transported after use (i.e., allowing for pre-disassembly).
	Design parts for disassembly stability
	Choose materials that can easily recover their original properties after recycling
	Protect fasteners from corrosion and wear
	Eliminate labels incompatible with the end-of-life treatment
	Provide information to the user on how the product or its parts are to be disposed of.

Continued

	Design guideline	**Justification for ruling out**
Both	Minimize the number of components.	Not clarity in the specific components.
	Minimize length of wires and cables.	They were assumed to be not problematic for SEDs.