

Design for Circularity Guidelines for the EEE Sector

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Abstract: The increased diversity and complexity of plastics used in modern devices, such as electrical and electronic equipment (EEE), can have negative impacts on their recyclability. Today, the main economic driver for waste electrical and electronic equipment (WEEE) recycling stems from metal recovery. WEEE plastics recycling, on the other hand, still represents a major challenge. Strategies like design ‘for’, but also the much younger concept of design ‘from’ recycling play a key role in closing the material loops within a circular economy. While these strategies are usually analysed separately, this brief report harmonises them in comprehensive Design for Circularity guidelines, established in a multi-stakeholder collaboration with industry leaders from the entire WEEE value chain. The guidelines were developed at the product and part levels. They are divided in five categories: (1) avoidance of hazardous substances; (2) enabling easy access and removal of hazardous or polluting parts; (3) use of recyclable materials; (4) use of material combinations and connections allowing easy liberation; (5) use of recycled materials. These guidelines are the first harmonised set to be released for the EEE industry. They can readily serve decision-makers from different levels, including product designers and manufacturers as well as policymakers.

Keywords: plastics; recycling; WEEE; design guidelines; design for recycling; design from recycling; circular economy

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1. Introduction

The annual global plastics production increased from 1.5 million tonnes in 1950 to 368 million tonnes in 2019 [1,2]. Ongoing innovation in the plastics industry has made it possible to use less material to deliver the same or better functionality. However, the increased diversity and complexity of plastics used in modern devices (such as electrical and electronic equipment (EEE)) has negative impacts on the later stages of a product’s lifecycle [3,4].

Waste electrical and electronic equipment (WEEE) is considered one of the fastest-growing waste streams in the EU and at the global level. According to the latest Global E-Waste Monitor, a record 53.6 million metric tonnes (Mt) of electronic waste was generated worldwide in 2019, up 21% in just five years [5]. Today, the main economic driver for WEEE recycling stems from the recovery of precious metals such as gold, silver, palladium, and copper. WEEE plastics recycling still represents a major challenge, since the plastic fraction is composed of a complex mix of many different polymers and additives. The dominant plastics in WEEE include acrylonitrile butadiene styrene (ABS), high-impact polystyrene (HIPS), polycarbonate (PC), PC/ABS blends, and polypropylene (PP) [3].

While recycling technologies in mechanical and chemical recycling have advanced in the past, the increasing complexity of the WEEE plastics mix makes it more challenging to recover all the different polymers, for technical or economic reasons [6]. More than 80% of the environmental impact of a product is determined at the design stage [7]. Therefore, the initial design of electrical and electronic equipment is key for recycling at their end of life, and design for recycling concepts are needed to meet the recyclers' feedstock requirements. However, not only design 'for' but also design 'from' recycling strategies play a key role in closing the material loop and reaching recycling targets [6].

As one part of the implementation of the first European Circular Economy Action Plan (CEAP) [8], the European Commission (EC) adopted a Europe-wide Strategy for Plastics in the Circular Economy in 2018 [9]. This strategy aims to transform how plastics and plastic products are designed, produced, used, and recycled in the future. Furthermore, the EC set the ambitious goal that 10 million tonnes of recycled plastics should find their way into new products on the EU market by 2025, as compared to the less than four million tons in 2016 [10]. The second CEAP, published in March 2020, reinforces the strategy towards more resource-efficient electronics and better plastics recycling [11].

Since stakeholder engagement will be crucial to reach this ambitious target, the EC launched the Circular Plastics Alliance (CPA) in 2018. The CPA brings together public and private stakeholders in the plastics value chain to promote voluntary actions and commitments for more recycled plastics. The stakeholders pledged to use or produce more recycled plastics, with the overall goal of reaching the 10 million tonne target by 2025. Furthermore, the CPA made the commitment to "develop, update or revise design for recycling guidelines for all plastic products and ensure they are revised on a regular basis to take into account innovation" [12]. A study conducted for the Joint Research Centre (JRC) of the EC in 2020 to establish a work plan to develop guidelines and standards on design for recycling of plastic products showed that many different guidelines exist for the packaging sector, but that specific readily available guidelines for the EEE sector are barely available [13].

To achieve sustainability-oriented innovation within the plastics industry that allows for increasing the share of recyclates in higher-value applications (such as new EEE), guidelines and standards on responsible design and minimum quality are needed [14]. This brief report aims to contribute towards filling this gap.

2. Materials and Methods

The topic of 'design for X' (DfX), where 'X' can represent numerous traits or features of a product or system including reliability, manufacturability, power, variability, cost, yield, environment, etc., has been broadly discussed in the scientific literature in recent decades. In the case of 'design for the environment', further distinctions can be made, e.g., in Design for Multiple Life Cycles [15], Design for Disassembly and Reassembly [16,17], Design for Remanufacturing [18–20], Design for Recycling [21], Design for End-of-Life [22], etc. A recent systematic literature review on 'design for X' approaches and how they address the circular economy research context was recently performed by Sassanelli et al. [23] and is not the focus of this brief report, which takes a more practical and industry-based approach.

A variety of practical guidelines to support design for plastics recycling has been published in grey literature in recent years, with an almost exclusive focus on the packaging sector [13,24–28], since packaging represents the highest demand for plastics and also generates most of the plastic waste [1]. Only a few practical and readily applicable guidelines focusing on EEE exist and these do not explicitly take into consideration the product development process on the product and part level and the use of recycled materials [21,29–31].

Design 'from' recycling is a younger concept aiming to incorporate recycled content in new EEE [32–34]. Some guidelines for the EEE sector are available, such as the Designing with Recycled Plastics booklet [35], which provides guidelines on the company level

to help manufacturers start using recycled plastics, or the Design from Recycling manual [36]. The latter has the objective of providing companies with the knowledge and support to design and produce products from recycled plastics and to estimate the sustainability of these products.

The concept of the Circular Economy is based on the idea of switching from linear thinking to circular thinking throughout the entire value chain. However, despite their inherent complementarity, the concepts of design ‘for’ and ‘from’ recycling are often treated separately. This is mainly related to the fact that two different ‘worlds’ operate almost independently of each other in practice: the world of product development (product designers and manufacturers) and the world of material recovery, which starts at a product’s end of life and involves waste collectors, sorters, and recyclers. Figure 1 illustrates the division between the two worlds, which can be bridged by design ‘for’ recycling at Gate A and design ‘from’ recycling at Gate B.

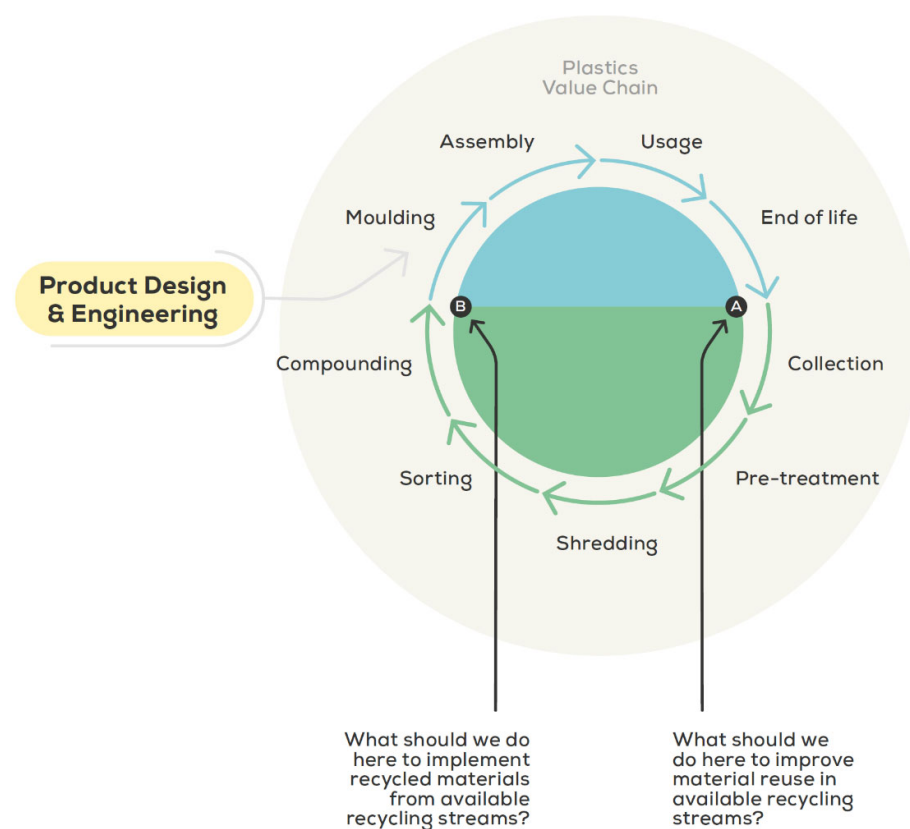


Figure 1. Bringing together the world of product development and the world of material recovery, according to the Pezy Group.

However, only by keeping in mind the connection of both ‘gates’ will it become possible to develop comprehensive Design for Circularity guidelines. For this purpose, a multi-stakeholder collaboration was established across the entire WEEE value chain within the H2020 project PolyCE, including—in addition to the authors’ organisations—the companies Philips (Original Equipment Manufacturer), Imagination Factory (product designers), Erion (Extended Producer Responsibility System), ecosystem (Extended Producer Responsibility System), MGG Polymers (WEEE recycler), SWEEEP Kuusakoski (WEEE recycler), Enva (recycler), and Sun recycling (recycler).

The first set of draft guidelines was established in close collaboration between Fraunhofer IZM and MGG Polymers and was presented at the Going Green CARE Innovation

2018 conference [37], where it was taken up by industry, in particular through the European Electronics Recyclers Association (EERA) [38]. In a second step, the guidelines were refined through an iterative improvement process with the manufacturer Philips. Philips had developed its own guidelines based on internal company research as well as years of experience working with numerous recyclers in different countries [21]. In a third step, the results were further improved through investigations including site visits at recyclers’ facilities and multiple expert interviews from the above-mentioned organisations. The guidelines are intended to reflect the latest status of WEEE collection and recycling in the EU but are written in a practical way to be applied by product designers who usually work on different levels. For this purpose, the guidelines are divided into a product level and a part level. The overall concept is shown in Figure 2.

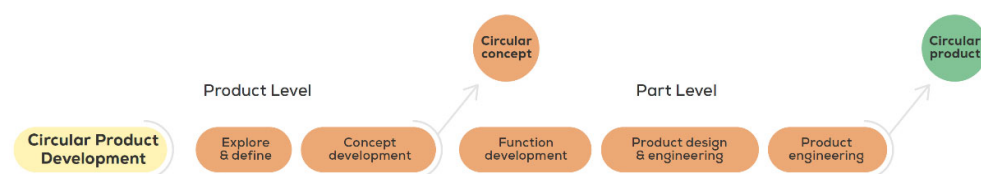


Figure 2. Concept of the design for and design from recycling guidelines, according to the Pezy Group.

On both levels, the guidelines are subdivided into:

1. Avoidance of hazardous substances
2. Enabling easy access and removal of hazardous or polluting parts
3. Use of recyclable materials that will be recycled by WEEE recyclers
4. Use of material combinations and connections that allow easy liberation
5. Use of recycled materials.

3. Results

3.1. Product Level—From Start to Concept

This sub-chapter provides guidelines on the product level, which typically covers the stages from the start of a project until the validation of the concept. The guidelines and the underlying rationale are summarised in Table 1.

Table 1. Design guidelines on the product level. WEEE: waste electrical and electronic equipment.

Guidelines and Design Strategies	Rationale
Enabling easy access and removal of hazardous or polluting parts	
Use click/snap solutions to fix batteries in a product. Avoid permanent fixing such as glued, welded, and enclosed solutions.	Annex VII of the WEEE Directive requires selective treatment for several materials and components, such as batteries, which should be removed from any separately collected WEEE stream [39]. If not detected and removed properly, batteries pollute the material streams and can explode during the recycling process. When using Li-ion batteries, hard cells should be preferred. Soft Li-ion batteries can be more easily damaged, which constitutes a safety and fire risk.
Fix valuable parts (e.g., printed circuit boards (PCBs), cables, wires, and motors) in a product with metal screws, click fingers, press-fit, shrink foil, self-screwed/tapering, or connectors. Avoid permanent fixings such as pressure sensitive adhesive (PSA) tapes, glue, and welded solutions.	Recycling is mainly driven by economic considerations. Facilitating the separation of valuable parts will lead to a higher yield and less loss in other material streams. Furthermore, Annex VII of the WEEE Directive requires selective treatment of PCBs with a surface greater than 10 square centimetres [39].
Use drains for operating liquids and gasses and enable easy removal of parts such as oil tanks, compressors, and hoses.	Some products contain operating liquids and gases that can be hazardous for humans and the environment (e.g., ozone-depleting substances). Annex

	<p>VII of the WEEE Directive requires selective treatment of chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) or hydrofluorocarbons (HFCs), and hydrocarbons (HCs) as well as gas discharge lamps [39].</p> <p>Ensuring safe but also easy to find drains or alternative solutions that enable the removal of such liquids and gasses should be considered at the design stage.</p> <p>In the case that drains cannot be implemented, specific markings indicating where the product can be opened can help recyclers during dismantling and depollution.</p>
Use detachment possibilities for hazardous and polluting parts/materials (e.g., dust bags, lamps, cord sets, cord winders, paper, cardboard, textiles, wood, foams, glass, and ceramics).	<p>It is important to provide detachment possibilities for hazardous and polluting parts since they could otherwise pollute the material streams. Annex VII of the WEEE Directive requires selective treatment of hazardous components such as polychlorinated biphenyls containing capacitors, electrolyte capacitors containing substances of concern, mercury containing components or components containing refractory ceramic fibres [39]. Providing detachment possibilities will facilitate compliance and can reduce recyclers' operating costs.</p> <p>In the case that this is not possible (e.g., for functional reasons), markings can help at the first stage of the dismantling/recycling process where the product breaks open.</p>
Use one module for hazardous parts in the product structure to enable taking out <u>one</u> non-recyclable module instead of searching for several different hazardous parts.	<p>Concentrating hazardous parts on one or very few modules facilitates the recycling process since it is easier for the recycler to detect them during the manual dismantling step instead of searching for multiple parts. This feature saves time and effort in the process, which can help reduce operating costs.</p>
Use of recyclable materials that will be recycled by WEEE recyclers	
Avoid thermosets and composites.	<p>Thermosets and composites cannot currently be recycled with existing technologies. When they are necessary (e.g., for functional reasons), materials outside the density range of commonly recycled plastics (0.85–1.25 g/cm³) should be preferred.</p>
Do not use plating, galvanizing, and vacuum-metallization as a coating on plastics.	<p>The mentioned techniques connect plastics with metals, a combination that cannot be separated in the recycling process.</p>
Avoid the use of coatings on plastics.	<p>All forms of coatings pollute the material stream or make the recycling process more challenging. Coatings change the density of the plastic, which can cause the plastic to end up in the wrong material stream. Printing numbers or lines for level-indication are not considered problematic and are usually better than using a sticker for the same purpose. Other options are screen-printing, in mould texturing or laser engraving.</p> <p>When a coating is still needed, a density difference <1% of the material's weight is acceptable. Multilayer lacquering should always be avoided.</p>
Minimise the use of thermoplastic elastomers.	<p>Thermoplastic elastomers are currently not recycled and have to be separated. Particles that are not separated pollute the waste stream.</p>
Avoid the use of foam.	<p>Foam can lead to issues during the recycling process. When foam is necessary (e.g., for functionality), thermoplastic foam should be preferred to foam from elastomers or thermosets.</p>
Minimise the use of magnets.	<p>Magnets end up in the ferrous material stream, leading to a pollution of the stream. For this purpose, the use of magnets should be reduced to a minimum when the functionality is required and no alternatives are currently available (e.g., neodymium magnets in mobile phones).</p>
Use of material combinations and connections that allow easy liberation	
Avoid moulding different material types together by multiple-K processes (different plastic materials injected into the same mould, over-moulding, or in-mould decoration).	<p>It is very challenging to separate different materials that have been joined by multiple-K processes. They will usually end up as residue or (depending on the density) pollute other plastic streams.</p> <p>If the material types are the same and only differ in colour and additives (e.g., moulding red PP containing antioxidants on black PP containing talc) multiple-K processes are not an issue.</p>

	An in-mould assembly by multiple-K processes that does not result in a chemical bonding of the materials is acceptable since the materials will be separated during shredding.
Avoid connections that enclose a material permanently. Avoid methods such as moulding-in inserts into plastics, rivets, staples, press-fits, bolts, bolt and nuts, brazing, welding, and clinching.	The mentioned processes are typical for tightly enclosing materials and should be avoided, if possible. Enclosing a material permanently makes separation more challenging and can pollute the recyclers' waste stream.
Use of recycled materials	
Consider more textured surfaces for injection moulded plastic parts. Avoid uniform high-gloss surfaces.	Traces of elastomers and glass reduce the quality of large high-gloss surfaces.

3.2. Part Level—From Concept to Production

This sub-chapter provides guidelines at the part level where the concept is brought to the concrete production of the product. This stage includes the function development, design, and engineering of the specific parts of the product and the production. The guidelines and their rationale are summarised in Table 2.

Table 2. Design guidelines at the part level. ABS: acrylonitrile butadiene styrene; PP: polypropylene; PC: polycarbonate; HIPS: high-impact polystyrene.

Guidelines and Design Strategies	Rationale
Avoidance of hazardous substances	
Avoid the use of brominated flame retardants (BFRs) such as polybrominated diphenyl ethers (PBDEs), tetrabromobisphenol A (TBBPA), polybrominated biphenyls (PBBs), Hexabromocyclododecane (HBCD), etc., in the product.	According to Annex VII of the WEEE Directive, plastics containing BFRs have to be removed from any separately collected WEEE [39]. Usually, they can be separated by recyclers and end up in incineration. Several BFRs are already restricted, and it is possible that more will be banned in the future. If these substances are used in materials today, it is likely that they will not meet the requirements to be recycled and reused in new products in the future (legacy substances).
Avoid the use of substances of very high concern (SVHC) according to the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Regulation [40] and substances classified as carcinogenic (Carc. 1A or 1B), mutagenic (Muta 1A or 1), or reprotoxic (Repr. 1A or 1B) by the Classification, Labelling and Packaging (CLP) Regulation in housing/housing parts [41].	If a substance is identified as a SVHC, it is included in the REACH Candidate List. The European Chemicals Agency (ECHA) regularly assesses the substances on the Candidate List to determine if they should be moved to the Authorisation List (Annex XIV). Once a substance is on an Authorisation List, it can only be used or produced with a specific authorisation and under specified circumstances for defined applications. If these substances can be avoided at the design stage today, they will not cause problems in future recyclates.
Avoid the use of substances that are listed on the 'SIN list' [42].	These substances are mainly used in plastics as surfactants, solvents, stabilizers, plasticizers, anti-corrosions, pigments, and coatings. They should not be used in concentrations above 1000 ppm, (0.1% per article) per substance. Background: The 'SIN' (substitute it now) list is a list of substances that are not yet restricted but are candidates for the SVHC list in the future (see above). SIN list substances represent an indication of substances to be restricted/banned in the future. If these substances are used in materials today, future waste stream might not meet the requirements to be recycled and reused in new products.
Do not use halogenated polymers (e.g., Polyvinyl chloride (PVC), Polytetrafluoroethylene (PTFE)).	PVC degrades at the typical processing temperatures of other polymers such as ABS, PC, PC/ABS, PP, PA (polyamide), and HIPS. The generated hydrochloride acid corrodes normal extruders and moulds.
Enable easy access and removal of hazardous or polluting parts	
Avoid magnetic parts on printed circuit boards (PCBs).	PCBs contain many valuable non-ferrous metals. If magnets are placed on the PCB, the entire board might end up in the ferrous stream. In this case, the valuable non-ferrous metals are lost and pollute the ferrous stream.
Use of recyclable materials that will be recycled by WEEE recyclers	
Use common plastics in the product such as ABS, PP, PA, PC, PC/ABS, HIPS, PE (polyethylene), where possible.	Common plastics can be easily recycled with existing technologies and processes and should be considered as a first choice. If other materials are required, the reasons should be motivated and supported. Other plastics currently occur in too small volumes for economically viable recycling [43].

	If other than the common plastics are used, alternatives outside the density range of 0.85–1.25 g/cm ³ should be considered to facilitate separation.
Avoid polymer blends.	<p>Mono-material streams should be favoured. Blends like</p> <ul style="list-style-type: none"> - POM/ABS (polyoxymethylene/acrylonitrile butadiene styrene) - PA/ABS (polyamide/acrylonitrile butadiene styrene) - PC/PBT (polycarbonate/polybutylene terephthalate) - PPE/PS (polyphenyl ether/polystyrene) - PET/PBT (polyethylene terephthalate/polybutylene terephthalate) <p>pollute material streams (except for PC/ABS, since it can be properly recycled with existing technologies).</p>
Avoid glass fibre-filled plastics.	Glass fibres pollute material streams, reduce mechanical properties (e.g., impact strength), and cause wear. For a high modulus, mineral filled plastics such as PP-talc should be considered, since they can be recycled. Carbon fibres are also considered a better alternative.
Minimise the use of thermoplastic elastomers.	Most of the elastomers can be filtered out during the separation steps. Those elastomers that are not filtered out are likely to end up in the PS stream. When elastomers are necessary (e.g., for functionality), minimise their use and choose, if possible, Styrol-Ethylen-Butylen-Styrol (SEBS) based thermoplastic elastomers (TPE). If a SEBS-based TPE ends up in the PS stream, it may act as an impact modifier, causing the least harm.
Avoid the use of thermoset rubbers.	Thermoset rubbers cannot be recycled and should be reduced, if possible.
Minimise additives in plastic materials.	Additives reduce the purity of the plastic streams. For this reason, the real necessity for additives should be evaluated cautiously.
Use material combinations and connections that allow easy liberation	
Avoid fixing ferrous metals to non-ferrous metals in either parts or fasteners. For example, do not use a screw (ferrous metal) to attach a part to aluminium (non-ferrous).	If a product that contains joined ferrous and non-ferrous materials goes into shredding, it is very likely that either the ferrous or the non-ferrous stream will be polluted. The materials are shredded into small pieces and either the screw will go with the host part to the non-ferrous stream or the non-ferrous part will follow the screw into the ferrous stream.
Do not permanently fix aluminium (Al), copper (including brass), stainless steel, or steel together in the following combinations:	
<ul style="list-style-type: none"> - If the main material in a part is Al (cast), do not attach a part of stainless steel, or steel on it. - If the main material in a part is Al (wrought), do not attach a part of Al (cast), copper, stainless steel, or steel on it. - If the main material in a part is stainless steel, do not attach a part of copper on it. - If the main material in a part is steel, do not attach a part of copper or stainless steel on it. - If the main material is copper, do not permanently fix a part of iron, lead, antimony, or bismuth to it. 	<p>The listed combinations are based on the thermodynamic properties of the materials, indicating which materials can be combined and which ones cannot. Depending on the main material in a part, smaller amounts of other materials will end up polluting the stream.</p> <p>Some materials are easy to separate, while others are rather problematic. A good and easily separable material combination will lead to less polluted material streams. Since polluted streams often end up as a waste fraction, this rule can also lead to waste prevention.</p>
Use of recycled materials	
Choose geometries for injection-moulded parts that allow easy flow paths. Avoid tight and narrow geometries.	High shear rates caused by narrow geometries can stress and degrade polymers.
For injection mould plastic parts, do not use long injection paths.	Recycled polymers are more sensitive to shear and temperature. A possible solution could be the use of multiple injection points. Consider increasing the wall thickness.
For injection mould plastic parts, consider more or wider venting ports.	Recycled polymers can have higher emissions during production due to pollutants or degrading polymers.
Use virgin plastics for very demanding parts (e.g., transparent light guides).	Recycled plastics are different from virgin plastics and cannot as yet meet every demanding requirement.

4. Discussion and Conclusions

The main objective of this brief report was to provide Design for Circularity guidelines for the EEE sector that include aspects of design ‘from’ recycling as well as design ‘for’ recycling, with a focus on the circularity of plastics. While these approaches handle the start and end of life respectively, they are not just complementary but also synergetic. Adherence to design for recycling is expected to reduce challenges faced in design from recycling, as problematic materials and components will have been reduced at least.

The topic of DfX strategies has been discussed in academic literature for many years, but practical and up-to-date guidelines that were co-constructed with and validated by industry leaders are scarce. The results presented in this report are the outcome of a perennial multi-stakeholder collaboration along the entire EEE manufacturing and WEEE plastics recycling value chain, including designers, original equipment manufacturers (OEMs), extended producer responsibility systems, and recyclers. The authors are aware that this is an unconventional approach in scientific literature. However, for any such guidelines to find a broad and willing uptake in the industry, these stakeholders need to feel engaged and to know that their practical day-to-day concerns have been considered and addressed. It is our firm belief that these guidelines, having been co-developed by leaders in EEE manufacturing and the recycling industry, are an important added value to future sector-wide acceptance and integration of the guidelines.

The guidelines provide practical rules and design strategies at the product and part levels and can help designers and manufacturers of EEE to improve the circularity of their products. As an example, they present a highly relevant input for the ongoing sector-specific work of the Circular Plastics Alliance that has the objective of boosting the EU market for recycled plastics to 10 million tonnes by 2025. In its declaration, the CPA made a commitment to “develop, update or revise design for recycling guidelines for all plastic products and ensure they are revised on a regular basis to take into account innovation” [12]. The guidelines developed in this report can readily serve as an input for the CPA for the EEE sector.

Furthermore, they can also be useful for policymakers as a direct technical input for policy instruments and initiatives to take better into account material efficiency aspects for a product category where the ecodesign focus has been mostly on energy efficiency so far [8]. As an example, the guidelines could be used as input for the ongoing revision of the Methodology for Ecodesign of Energy-related Products (MEErP) which is planned to be finalised by the end of 2021. Moreover, the findings could contribute to possible future product-specific standardisation work as a follow-up of the recently published CEN/CLC/JTC 10 horizontal standards on material efficiency aspects for ecodesign of energy-related products and in particular the general methods for assessing the recyclability and recoverability of energy-related products (EN 45555:2019) [44]. In line with the revision of the MEErP and recent standardization work, the present guidelines could also be taken up by the Sustainable Products Initiative that will revise and extend the Ecodesign Directive and propose additional legislative measures to make products placed on the EU market more sustainable [45].

To the best of our knowledge, the guidelines present the current state of the art. However, since materials and processes are constantly evolving, they should be seen as a living document and might need to be updated in the future. Future research could furthermore analyse requirements and opportunities for cluster-specific guidelines, e.g., being based on the categories of electrical and electronic equipment defined in Annex III of the WEEE Directive [39].

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