Resources, Conservation & Recycling Advances 21 (2024) 200207

Contents lists available at ScienceDirect

Resources, Conservation & Recycling Advances

journal homepage: www.sciencedirect.com/journal/Resources-Conservation-and-Recycling-Advances

The role of product design in advancing the circular economy of electric and electronic equipment

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ARTICLE INFO

Keywords:
Circular economy
Electric and electronic equipment
Minimum entropy model
Product design

ABSTRACT

Circular economy (CE) processes, such as reuse, remanufacturing, and recycling, play a significant role in reducing the environmental impacts of modern manufacturing industries. However, electric and electronic equipment (EEE) is still often designed to function for a short usable life after which it is discarded. Furthermore, the current relatively low price and high availability of virgin raw materials, compared to those of recycled materials, decrease the financial viability of recycling. This study conducts a systematic literature review on product design-related issues in the CE of EEE and induces a novel model of product design considerations for the CE of EEE. The aim is to identify design traits that are hindering the CE of EEE and what measures can be taken in the product development phase to create EEE compatible with CE. This study points out general issues in the disassemblability and recyclability of EEE, as well as a recurring theme of conflicting design needs between different CE processes. Furthermore, the minimum entropy product design priority model is introduced as the novel contribution of this study to highlight the dependency between technological maturity, expected product lifespan, and suitable CE processes.

1. Introduction

The amount of waste electric and electronic equipment (WEEE) produced in the world is growing at an alarming rate. WEEE contains numerous hazardous materials, which makes improper disposal of it a significant risk for the environment and human health (Forti et al., 2020). Moreover, the composition of WEEE is not stable, because the devices that constitute WEEE change with each technological cycle, and old generations of devices are discarded as obsolete or defective (Cucchiella et al., 2015). Even though virgin raw materials are currently relatively inexpensive and rather well available, recycling the materials in WEEE is becoming more interesting as the price and scarcity of the materials they contain, especially rare-earth minerals and metals, are rising along with demand (Gislev and Grohol, 2018). For some materials, such as lithium and cobalt used in batteries for devices and electric vehicles (EV), there are major challenges in ensuring a sustainable supply to meet future demand (e.g. European Commission, 2020; Hu et al., 2021).

Some of the most prominent issues in WEEE are challenges with handling certain materials, such as high-tech plastics, which likely end up as landfill (Cucchiella et al., 2015). Potential solutions have been developed to these issues (e.g., Birloaga and Vegliò, 2022; Dassisti et al., 2017), but the recycling rate of these materials remains low (Haarman et al., 2020). The recovery of precious metals from WEEE is also an ever-changing field: as the products themselves evolve, the waste they end up creating is different to that created by previous generations of products (Cucchiella et al., 2015; Sthiannopkao and Wong, 2013). This issue is closely related to the technological maturity of the products in question, i.e., the level of technological development during the products' expected lifespan (e.g., Nolte, 2008, pp. 7–17). Disposing of and recycling electronic products also comes with risks. At worst, WEEE are shipped to countries with emerging economies where the risk of improper recycling methods or disposal can cause significant harm to the local environment and communities (Awasthi et al., 2019; Sthiannopkao and Wong, 2013).

The harm caused by overextraction of raw materials, production of electric and electronic equipment (EEE), and handling of WEEE is a serious issue for the environment and communities affected by these issues; hence, different solutions have been called for to limit their effect. One proposed solution to the growing issue of WEEE is to utilize circular economy (CE) principles in the design, use, and disposal of EEE (Aminoff and Sundqvist-Andberg, 2021). Traditional business models

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https://doi.org/10.1016/j.rcradv.2024.200207

usually revolve around linear economy business models, where raw materials, assemblies, and products are designed to go through a linear usable lifespan and end up being disposed of. CE business models and processes, in contrast, aim to reconnect the material streams previously considered waste to the production of new products so that the outputs of other processes end up as inputs for others (Korhonen et al., 2018). This strategy is known as closing the loop (e.g. (Mestre and Cooper, 2017). This minimizes the creation of waste and decouples the material needs of production from the extraction of raw materials. The CE also aims to slow the flow of materials by lengthening products' usable lifespans by making them last longer in their primary use and introducing a second usable life after the first one. This enables the value of extracted materials and used resources to be sustained for longer than in a linear economy (Bocken et al., 2016; Mestre and Cooper, 2017).

One area of interest for the CE is what the European Union's Waste Framework Directive (2008) terms "preparing for re-use," which consists of methods for continuing a product's usable lifespan by delaying its end-of-life (EOL), including reuse, repurposing, repairing, refurbishing, reconditioning, and remanufacturing (e.g. Gharfalkar et al., 2015; King et al., 2006; Pérez Martínez et al., 2021). Although recycling also keeps materials in circulation, it is less desirable than preparing for reuse, as the products themselves are destroyed in the recycling process, and more energy is needed to recover them to a usable form (King et al., 2006). The new proposal for Ecodesign for Sustainable Products Regulation by the European Commission also aims to further direct industries towards CE principles by highlighting, for example, product durability, reusability, upgradeability and repairability as well as demanding more information to be available from producers to enable these CE related activities (European Commission, 2022a)

Even though CE is preferable to linear material flows, companies manufacturing EEE are generally ill-prepared for the transition to a more circular flow of materials: Many electronic devices suffer from short lifespans (Babbitt et al., 2009; Kastanaki and Giannis, 2022), poor repairability (Bracquené et al., 2021; Cordella et al., 2021), and abundant use of hazardous materials in EEE (Cucchiella et al., 2015). Also, even though the electricity consumption of newer EEE products can be lower than that of their older counterparts, replacing them prematurely can be more environmentally detrimental than extending their lifespan (e.g., Bakker et al., 2014). Product design (PD) plays an essential role in the early intervention to these issues, as up to 80 % of the environmental effects of products is determined in the design phase (European Commission, 2022b), and the choices made in PD have a significant effect on the circularity of products (e.g. Charles et al., 2016; Bovea and Pérez-Beliz, 2018). Designing products to better suit the demands of CE is drawing increased attention (e.g. Bocken et al., 2016; de Kwant et al., 2021; Sassanelli et al., 2020). PD itself is a sub-process of product development, in which the product is formed to meet the various and often conflicting requirements set to it by different stakeholders (Kuo et al., 2001). PD can be guided by design goals and parameters, for example by using Design for *X* (DfX) approaches, such as Design for Sustainability, -Reliability, Disassembly and Reassembly, or -Product Service Supportability (Sassanelli et al., 2017, 2020). These approaches guide PD by systematically addressing the given requirements, and steering design choices towards reaching them (Sassanelli et al., 2020). Mestre & Cooper (2017) suggest, that to achieve truly sustainable design, the technological cycle of CE (slowing and closing material loops) should be complemented with considerations towards the biological cycles of products through bio-inspired and bio-based strategies. This includes utilizing, for example, biomimicry or the use of bio-based materials to achieve products better suited to different processes of the CE. Although prior studies have examined issues in the design of CE products, as shown in Table 1., there are still research gaps in finding preferable PD approaches to meet the CE goals in different types of EEE. Therefore, this paper aims to contribute to the literature by studying the role of PD in the CE of EEE using the Waste Framework Directive's (2008) concepts of "preparing for re-use" and recycling as a focus point. With that scope, CE processes such as refusing (i.e., making a product redundant) or reducing (i.e., using fewer natural resources) discussed in the literature (e.g., Morseletto, 2020) are excluded from this study. Thus, this paper reviews the current literature to study the limiting factors to CE in the PD of EEE and what measures can be taken to improve it. Thus, the first question this article attempts to answer is:

Table 1
Key related literature reviews compared to this study.

Author(s)	Years included	Databases	Products studied	Focus of study
de Kwant et al. (2021)	–2021	Scopus	EVs, white goods	The role of design in the circular economy of EVs and white goods and how they affect circular business models
Sassanelli et al. (2020)	1999–2019	ScienceDirect, Scopus	Not limited to certain products	How design affects CE transition through DfX approaches
Spreafico (2022)	2010–2021	Scopus, Google Scholar	Not limited to certain products	Hierarchy of CE processes in sustainability, design strategies with greatest environmental benefits
This study	2014–2022	Scopus, Web of Science	EEE	What is hindering the CE of EEE, what measures can be taken in the PD phase to create EEE that are compatible with CE

RQ1: What product design-related challenges are currently hindering the CE of EEE?

The issues related to the CE of EEE are studied by reviewing the state-of-the-art literature. The review reveals not only research gaps in the literature, but also recurring themes, which can indicate PD considerations that can enhance the circularity of EEE. Furthermore, the entropy-based hierarchy of CE processes (Stahel, 1994; King et al., 2006) is further elaborated in this study to create a novel model that can be utilized in determining suitable CE processes for EEE. These results answer to the second research question:

RQ2: What measures can be taken in the product design phase to create EEE that are compatible with CE?

In summary, the aim of answering RQ1 and RQ2 is to examine the known challenges in the CE of EEE equipment and identify design considerations that help enable the CE of EEE.

This paper is structured as follows. The research methodology is discussed in Section 2. Section 3 presents the results of the study, and Section 4 discusses the key findings and their implications along with conclusions.

2. Methodology

The research method used in this study is a systematic literature review, as described by Seuring & Müller (2008), which consists of four steps:

1. Material collection
2. Descriptive analysis
3. Category selection
4. Material evaluation

The first step consists of defining and delimiting the materials and scope of the study. In this study, this is done by formulating search parameters in the Scopus and Web of Science databases to ensure a suitable number of relevant studies is included, as described in Section 2.1. The second phase is addressed in Section 2.2, where the studied material is discussed in terms of formal aspects. The third step is conducted in Section 2.3, where the material is further evaluated and categorized according to findings made from it. The fourth stage is also addressed in Section 2.3, where the created structures are evaluated and analyzed.

2.1. Material collection

After consulting a university library information specialist about the research process and a material collection plan, the material for this review was retrieved from the Scopus and Web of Science databases in October 2022 and updated with new database searches in January 2024. Broad search terms and inclusion of wide subject areas were utilized to ensure that a wide variety of articles were included for screening. Types of devices, such as smartphones or personal computers, were not specified in search terms, as no specific devices were targeted in this study. Further processing of the material relied on title, abstract, and full text screening to only include articles that include implications on the subject area. The large amount of manual screening in this phase was done to ensure that articles selected for full-text review would be relevant and fit the intended subject area (Rožanc, 2018). Wildcards and multiple choices of terminology were used to further make sure that articles on the subject were included in the search. The search terms used were chosen to link instances where the terms *electronics* or *electric* were used with *reuse, repurpose, repair, recondition, refurbish, remanufacture* or *recycle* in the title, abstract, or keywords. The objective in choosing keywords was to include a large number of studies from many scientific areas which could be narrowed down thematically to fit the study. The search string used for both Scopus and Web of Science was (electroni* or electri*) AND (reus* OR repurpose* OR repai* OR reconditio* OR refurbis* OR remanufactur* OR recycl*).

The large number of results (tens of thousands of articles in both Scopus and Web of Science) was then narrowed down by limiting results to journal articles written in English, filtering out unrelated subject areas – Chemistry, Chemical engineering, Computer science, Mathematics, Agrology, Medical sciences, Biochemistry, and Immunology were excluded – and further refining the search to articles where *"circular economy"* appeared in the title, keywords, or abstract. The objective of this filtering was to exclude studies that were not thematically connected to the CE of EEE.

The resulting studies were exported to Covidence (https://www.covidence.org/) to remove duplicates and for title and abstract screening. At this stage papers without a focus on the PD of EEE were filtered out. This step narrowed the number of articles down considerably, as the number of papers not explicitly stating CE, EEE, or implications to PD was large. This stage also had the highest risk of selection bias affecting the selected articles, which was mitigated by utilizing clear inclusion criteria (Tranfield et al., 2003). Due to the scope of this study, the following inclusion criteria was used: the articles to be included in the full text review phase had to discuss either the effect of PD in the CE of EEE or the effect of external requirements on the subject (regulatory effects, customer opinions, business environment, etc.) in their title or abstract. If the article did not fulfill these criteria, it was filtered out. A full text review was then conducted to produce the final results of the material collection. Articles that did not address PD issues in the CE of EEE were excluded at this point, as well as articles without full text availability. The full process of the material collection is visualized in Fig. 1.

The material collected through this process consists of 44 research articles. The full results, along with the types of products, CE processes addressed, and geographical focus, are described in Table 2.

2.2. Descriptive analysis

This section addresses the bibliometric analysis of the selected articles.

Articles were not filtered by year of publication in the material collection phase, but the selected search terms and filtering produced relatively new articles. The oldest article in the study is by Bakker et al. (2014), which, although old compared to the rest of the collected material, was still deemed relevant. All the other articles were published between 2017 and 2023. The full distribution of articles per year of publication can be seen in Fig. 2.

The selected material was published in 20 different journals. *Journal of Cleaner Production* was the most common journal, with 14 articles, followed by *Sustainability*, with six articles, and *Resources, Conservation*

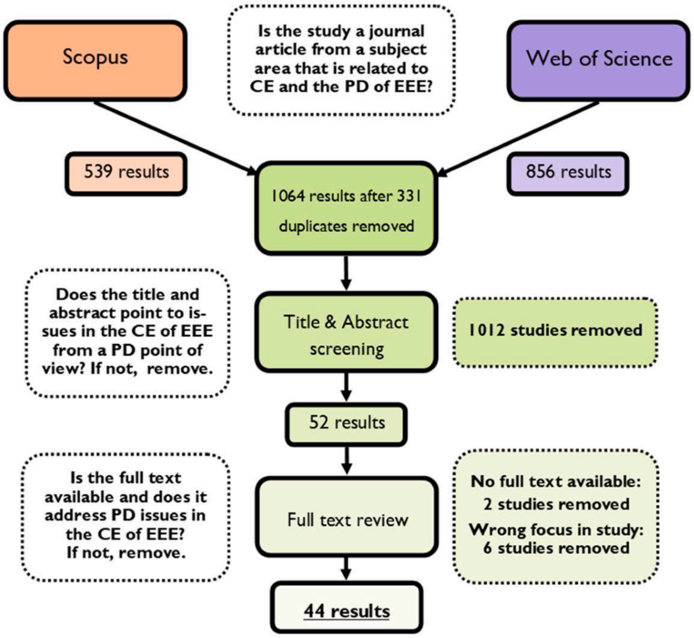

Fig. 1. Visualization of material collection methods (modified from Page et al., 2021).

Table 2
Collected material.

Paper	Journal	Research method	Type of product	Geography of study
Ahuja et al. (2020)	Journal of Property, Planning and Environmental Law	Regulatory review	EV batteries	United Kingdom
Akasapu & Hehenberger (2023)	Journal of Cleaner Production	Life cycle assessment	EV batteries	Global
Albertsen et al. (2021)	Resources, Conservation and Recycling	Multiple case study	EV batteries	Europe
Alkouh et al. (2023)	Electronics	Mixed method	Oil and gas production EEE	Persian Gulf
Atlason et al. (2017)	Journal of Cleaner Production	Quantitative survey	EEE	Denmark
Bakker et al. (2014)	Journal of Cleaner Production	Case study	Refrigerator/freezer, laptop	Netherlands
Berwald et al. (2021)	Sustainability	Multiple case study	EEE	Europe
Bovea & Pérez-Belis (2018)	Journal of Environmental Management	Case study	EEE	Spain
Bracquené et al. (2021)	Journal of Cleaner Production	Case study	Washing machine	Europe
Bundgaard & Huulgaard (2019)	Business Strategy and the Environment	Case study	EEE	Denmark
Canals Casals et al. (2019)	Journal of Cleaner Production	Case study/technical requirements & economic conditions study	EV batteries	Spain
Chen & Rau (2023)	Journal of Cleaner Production	Mixed method	Small household appliances	Global
Chouinard et al. (2019)	Journal of Cleaner Production	Literature review, survey	Mechatronics	Canada
Cole et al. (2019)	Resources, Conservation and Recycling	Interpretive synthesis	EEE	United Kingdom
Conti & Orcioni (2020)	Energies	Probability modeling	Elevator control system, PCB	Italy
Cordella et al. (2021)	Journal of Cleaner Production	Technical analysis	Smartphone	Europe
Coughlan et al. (2018)	Journal of Cleaner Production	Feasibility study	Notebook computers	Ireland
Singh et al. (2021)	Sustainability	Life cycle assessment	Photovoltaics	Australia
Deviatkin et al. (2022)	Sustainability	Multiple case study	EEE	Finland
Doyle et al. (2023)	Sustainability	Review of literature and patent databases	Energy harvesting platform	Global
Ferrara et al. (2021)	Advanced Energy and Sustainability Research	Life cycle assessment	Lithium batteries	Europe
Golsteijn & Valencia Martinez (2017)	Journal of Engineering	Life cycle assessment	WEEE	Netherlands
Hansen & Revellio (2020)	Journal of Industrial Ecology	Multiple case study	Smartphone	Austria, Germany
Huster et al. (2022)	Journal of Cleaner Production	Discrete event simulation, case study	EV batteries	Germany
Jerome et al. (2023)	Resources, Conservation and Recycling	Life cycle analysis	High voltage electric motors	Europe
Karagiannopoulos et al. (2022)	Energies	Multiple scenario simulation	Dishwasher, washing machine	Europe
Lampón (2023)	Sustainable development	Case study	EV	Europe
Lander et al. (2023)	Applied energy	Design analysis	EV batteries	Global
Mugge et al. (2018)	Design Journal	Experimental study, post hoc interviews	Smartphone	Netherlands
Mulvaney et al. (2021)	Renewable & Sustainable Energy Reviews	Literature review & case studies	Photovoltaics, wind turbines, lithium batteries, EV	Global
Norgren et al. (2020)	Journal of Sustainable Metallurgy	Review of literature and industry	Photovoltaics, wind turbines, lithium batteries, EV	USA
Parajuly & Wenzel (2017)	Sustainability	Feasibility study	WEEE	Denmark
Talens Peiró et al. (2017)	Journal of Industrial Ecology	Multiple case study	Lithium batteries	Europe
Pozo Arcos et al. (2020)	Journal of Cleaner Production	Multiple case study	Kitchen blender, refrigerator, vacuum cleaner	Global
Sahjawalla & Hossain (2023)	MRS Bulletin	Literature review	WEEE, energy storage units, solar panels	Global
Shahbazi et al. (2021)	Sustainability	Multiple case study	EEE	Sweden
Shi et al. (2023)	Nature materials	Mixed method	Smart textiles	Global
Svensson-Hoglund et al. (2021)	Journal of Cleaner Production	Literature review	EEE	EU/US
Tecchio et al. (2017)	Journal of Cleaner Production	Literature review & multiple case study	Electronic displays, washing machine	Europe
Thompson et al. (2021)	Resources, Conservation and Recycling	Comparative assessment	Lithium batteries	United Kingdom
Vanegas et al. (2018)	Resources, Conservation and Recycling	Case study	LCD monitor	Europe
Vogt Duberg et al. (2020)	Journal of Cleaner Production	Case study	Robotic lawn mower	Sweden
Williams & Shittu (2022)	Detritus	Literature review & SWOT analysis	EEE	Global
Yamamoto & Murakami (2022)	Waste Management	Questionnaire & statistical analysis	Personal computers	Japan

and Recycling, with five articles. Other journals had one or two articles each, as seen in Fig. 3.

The search string used included seven different CE processes, of which six emerged as clear themes in the material. For a CE process to count as being addressed, a mere mention of it within the text was not deemed sufficient. If a CE process was addressed in more detail, it was counted. A graph of the number of times CE processes were addressed is presented in Fig. 4.

2.3. *Category selection and material evaluation*

The scope of the study and types of articles chosen for it make for two

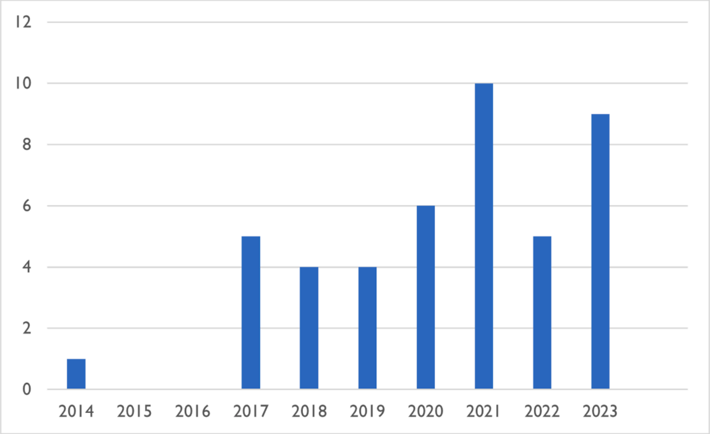

Fig. 2. Number of articles per year of publication.

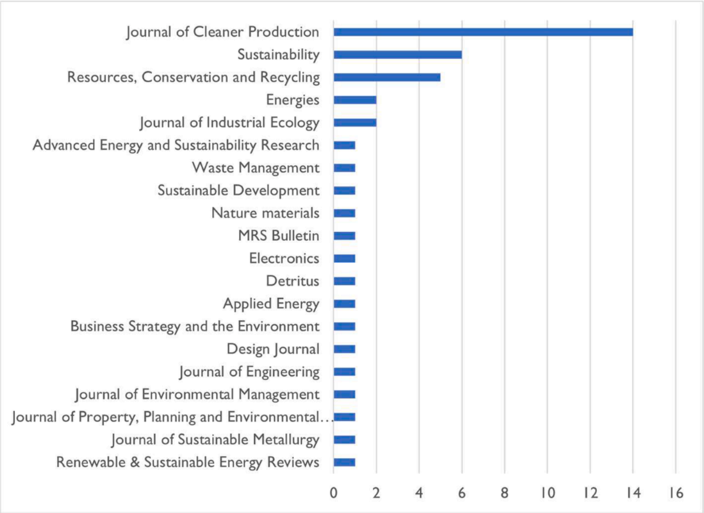

Fig. 3. Number of articles per journal.

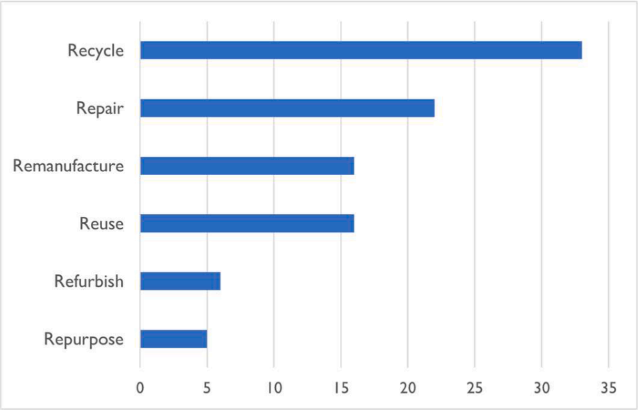

Fig. 4. CE processes addressed in the articles.

interesting dimensions to be studied: type of CE process addressed, and product types studied. Some articles address multiple CE processes or product types, so these dimensions provide a good amount of useful data in relation to the number of articles included in the study.

As there is some variance in some of the terminology used in CE, it is important to define the meaning of terms for this study. For this study, repairing is defined as extending a product's lifespan by restoring functionality and does not include activities that improve the product's original functionality (e.g. Fernandez and Kekäle, 2005; King et al., 2006). For example, replacing a mobile phone's cracked screen to restore its usability can be considered a repair.

The concepts of refurbishing, reconditioning, remanufacturing, and reusing are used in the literature quite liberally and with different meanings (Gharfalkar et al., 2015; Reike et al., 2018). All these terms, as well as reuse, repurpose, and recycle, are used in this study in a way that fits the existing literature and the study, as their differences ascribed to them, however slight, have a big impact in how the products are used in a CE concept.

Reuse has been used as an umbrella term to describe different ways of continuing a product's lifespan (European Parliament and Council, 2008; Gharfalkar et al., 2016) as well as to describe the use of a product or part without alteration after it has been retired from its original use, for example as a second-hand product (Pigosso et al., 2010). This is also the definition used in this study. If the product or part is used in a different application than that for which it was originally intended, for example using components from EOL computers in industrial applications, as in Pérez-Martínez et al. (2021), the term used is repurposing. There is considerable overlap in how the terms refurbishing and reconditioning are used in the literature, and in some cases they are used as synonyms (e.g. Hollander et al., 2017). For example, Mugge et al. (2017) define refurbishing as: *"[…] the process of returning a used product* *(e.g., smartphone) into a good working condition, by cleaning, replacing and/or repairing major components (such as the smartphone's screen or battery) that are faulty, damaged or close to failure and making cosmetic changes to update the appearance of a product."* This is close to the definition of reconditioning given by King et al. (2006), apart from cosmetic changes, which the latter authors do not discuss. For this study, these terms will be considered interchangeable, and the term refurbishing will be used to describe this process. Refurbishing and repairing are somewhat similar in function, but they differ in the extent and intent of the work done to the product: Repairing addresses acute issues that inhibit the normal use of the product, while refurbishing aims to restore the product to a fully working state and addresses probable future issues that have not yet been discovered.

Remanufacturing is the process of turning a used product into one that is indistinguishable from a new one by utilizing usable parts from used products, repaired parts, and new parts (Ferrer and Clay Whybark, 2000; Hatcher et al., 2011; Johnson and McCarty, 2014). In addition to resembling a new product functionally and aesthetically, remanufactured products usually have similar warranty policies to those of new products (Liao, 2018).

Recycling differs from the previously mentioned points in that in this process the original product is fully destroyed to utilize the raw materials used in it to be circulated back into the raw material stream of industries (King et al., 2006). In the context of electronic products, this usually means the recycling of plastic and metals used in the product's construction and components.

Building on previous literature, mainly on Stahel's (1994) model of self-replenishing loops, King et al. (2006) introduced the principle of least entropy to product life-cycle management, which prioritizes processes that slow material flows and preserve the value of products. This means prioritizing processes such as reusing, repairing, and remanufacturing over recycling. In line with this, Table 3 presents the studied CE processes and their definitions as well as examples used in this study in the order suggested by Potting et al. (2017).

The above schema was used to categorize articles according to how they addressed these processes. Merely mentioning CE processes in the introduction, for example, was not enough to attribute an article to a CE process; the study itself had to address the process to be granted the attribution.

Some of the articles focus on very particular product groups (e.g. Cordella et al., 2021), while others, such as Svensson-Hoglund et al. (2021), have a broader scope in EEE. As the varying scope of studies made it hard to compare results and themes between studies, a way to categorize results was needed. Four distinct product groups were thus constructed from the material:

Table 3
CE processes and their definitions (modified from Potting et al., 2017).

Process	Definition	Example
Reuse	Using a product or component for a second lifecycle without altering it	Second-hand products
Repair	Extending a product's lifecycle by returning it to a functional state	Replacing a faulty dishwasher water pump
Refurbish	Extending a product's lifecycle by returning it to a functional state as well as addressing possible future failure modes	Inspecting and refurbishing smartphones
Remanufacture	Recovering usable parts from EOL products, replacing consumables and unusable parts, and assembling them to create like-new products	Fully rebuilding robotic lawn mowers from used and new parts
Repurpose	Using a product or component for a second lifecycle in an application for which it was not originally designed	Using EOL EV batteries in power storage applications
Recycle	Recovering invested materials from products by removing and utilizing them as raw materials in new products	Using critical raw materials from EOL photovoltaics as a material input for producing new products

1. General EEE (EEE, WEEE, smartphones, vacuum cleaners, kitchen blenders, robotic lawn mowers, notebook computers, laptops, LCD monitors, and electronic displays).
2. White goods (refrigerators, washing machines, and dishwashers).
3. Industrial EEE (photovoltaics, wind turbines, mechatronics, elevator control systems, printed circuit boards).
4. Batteries (lithium batteries, EV batteries).

The General EEE group was chosen as a general product group described as consumer products that are powered either directly via mains power, for example vacuum cleaners or kitchen blenders, or by rechargeable batteries, as in the case of laptop computers or smartphones. This group represents general consumer devices, which were the most prevalent in this study.

White goods were chosen as the second group. White goods are considered large, usually non-portable, household appliances that are mains-powered and used for household work such as cooking, refrigeration, washing dishes, or laundry. This group was chosen because of their prevalence in the material and their unique attributes in CE.

Industrial EEE, the name of the third product group, was chosen as a general term for equipment that is generally not for consumers and usually has a long working life. This product group also includes parts or assemblies within products, such as in wind turbine blades (e.g. Mulvaney et al., 2021).

Finally, batteries were chosen as a distinct product group for this study because many of the studies selected addressed issues related to them. The articles in this product group discuss lithium batteries from EV applications (e.g. Ahjua et al., 2020) or lithium batteries in general (e.g. Thompson et al., 2021)

The product groups and CE processes addressed in the selected articles can be seen in Table 4.

Materials were collected and categorized systematically, and the created categories were induced from the material by comparing it to the literature. Doing so resulted in categories that delimit the material in two dimensions: the CE process addressed and the product type in question.

3. Results

The findings from the collected material are presented in this section. Section 3.1 and its subsections address the created product groups. General findings and emerging themes, as well as other interesting findings, are pointed out.

3.1. Themes within product groups

This section discusses results within the set product groups. CE processes overlap in the selected articles, so issues addressed are rarely limited to a single CE process.

3.1.1. General EEE

Recycling was the most common CE process in the general EEE product group, being discussed by 16 articles, followed closely by repairing, with 13 articles (Fig. 5). The results indicate, that contaminated recycled material cause recycling issues due to the difficulty of accessing and liberating hazardous or problematic materials (Berwald et al., 2021; Golsteijn and Valencia Martinez, 2017) and reveal limited value in recycling in current business models that encourage circular PD (Deviatkin et al., 2022). Both Vanegas et al. (2018) and Tecchio et al. (2017) found that the lack of standardization hinders the disassemblability and thus recyclability of general EEE. Doyle et al. (2023) suggests design for disassembly and deliberate material and production method

Table 4
Selected articles with product groups and CE processes.

Paper	Product group	Reuse	Repair	Refurbish	Remanufacture	Repurpose	Recycle
Ahuja et al. (2020)	Batteries		•			•	•
Akasapu & Hehenberger (2023)	Batteries						•
Albertsen et al. (2021)	Batteries		•	•	•	•	•
Alkouh et al. (2023)	Industrial EEE		•		•		•
Atlason et al. (2017)	General EEE	•			•		•
Bakker et al. (2014)	General EEE, white goods			•	•		•
Berwald et al. (2021)	General EEE						•
Bovea & Pérez-Belis (2018)	General EEE	•	•		•		•
Bracquené et al. (2021)	White goods		•	•			
Bundgaard & Huulgaard (2019)	General EEE	•	•		•		•
Canals Casals et al. (2019)	Batteries					•	
Chen & Rau (2023)	General EEE	•	•		•		•
Chouinard et al. (2019)	Industrial EEE	•		•	•	•	•
Cole et al. (2019)	General EEE	•					
Conti & Orcioni (2020)	Industrial EEE	•	•				•
Cordella et al. (2021)	General EEE		•				
Coughlan et al. (2018)	General EEE					•	
Singh et al. (2021)	Industrial EEE						•
Deviatkin et al. (2022)	General EEE	•	•		•	•	•
Doyle et al. (2023)	General EEE		•				•
Ferrara et al. (2021)	Batteries	•			•		•
Golsteijn & Valencia Martinez (2017)	General EEE						•
Hansen & Revellio (2020)	General EEE	•	•		•		•
Huster et al. (2022)	Batteries				•		
Jerome et al. (2023)	Industrial EEE		•				•
Karagiannopoulos et al. (2022)	White goods		•				
Lampón (2023)	Batteries						•
Lander et al. (2023)	Batteries						•
Mugge et al. (2018)	General EEE			•			
Mulvaney et al. (2021)	Industrial EEE, batteries						•
Norgren et al. (2020)	Industrial EEE, batteries						•
Parajuly & Wenzel (2017)	General EEE		•				•
Talens Peiró et al. (2017)	Batteries	•	•		•		•
Pozo Arcos et al. (2020)	General EEE, White goods		•				
Sahajwalla & Hossain (2023)	General EEE, Industrial EEE	•					•
Shahbazi et al. (2021)	General EEE				•		
Shi et al. (2023)	General EEE	•	•				•
Svensson-Hoglund et al. (2021)	General EEE		•				
Tecchio et al. (2017)	General EEE, white goods		•				•
Thompson et al. (2021)	Batteries						•
Vanegas et al. (2018)	General EEE	•	•				•
Vogt Duberg et al. (2020)	General EEE				•		
Williams & Shittu (2022)	General EEE	•	•	•	•		•
Yamamoto & Murakami (2022)	General EEE	•					
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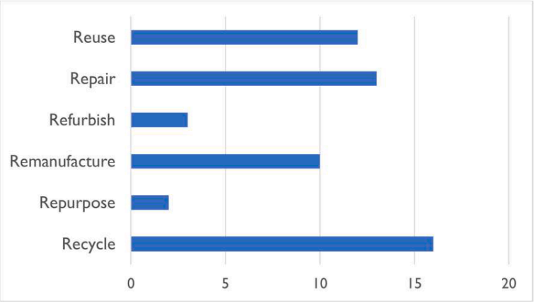

Fig. 5. Frequency of CE processes addressed in the general EEE product group.

choices to enhance the recyclability of general EEE. The results propose two solutions to standardization, Vanegas et al. (2018) suggested generic disassembly standardization, while Tecchio et al. (2017) proposed a product type-specific as well as overarching, more generic, standards concerning CE. Modularity was also suggested by Chen & Rau (2023), who propose five main DfX design criteria for CE of general EEE: recycling, reuse, remanufacturing, disassembly, and repair and maintenance, along with forty design elements from the perspective of product life cycle and WEEE processing.

Other issues found in repairing general EEE were legislative differences between geographical market areas (Svensson-Hoglund et al., 2021); lack of integration between original equipment manufacturers (OEM) and third-party circular service providers, which resulted in the unavailability of spare parts and information needed in circular activities (Hansen and Revellio, 2020); PD that does not allow the product's usable lifespan to be lengthened (Bovea and Pérez-Beliz, 2018; Deviatkin et al., 2022); and difficulties in fault diagnosis (Pozo Acros et al., 2020). On the other hand, a product family approach to PD was found to improve the repairability and recyclability of general EEE products (Parajuly and Wenzel, 2017), but Cordella et al. (2021), showed that repairability and reliability are not always correlated. This points out that designing CE products needs clear goals, as different processes in CE can have competing design requirements.

Remanufacturing was also quite prominent in articles about general EEE, being addressed in 10 papers. Of these, two articles exclusively discussed remanufacturing activities. Key issues found were largely in line with articles which also discussed other CE processes. These included issues with PD being unsuitable for remanufacturing (Bovea and Pérez-Beliz, 2018) and end users' perception of reused products (Atlason et al., 2017). Vogt Duberg et al. (2020) pointed out that design for remanufacturing (DfReman) is a supporting factor in transitioning to remanufacturing in an OEM setting, but they saw reverse logistics, labor skill and availability, remanufacturing facilities, remanufacturing process technology, and other supporting factors as more important than DfReman. This points out to process development being in an important role in remanufacturing general EEE products. Shahbazi et al. (2021), on the other hand, argued that the potential of automated remanufacturing and designing products for it are largely untapped in the CE of general EEE.

A few articles in particular stand out as interesting cases in extending the lifespans of general EEE with design implications. Bakker et al. (2014) found a link between the maturity of technology and suitable CE processes: newer, faster-developing products tend to benefit more from design for remanufacturing or -refurbishing than products utilizing more mature technologies – they can be developed to be more robust and repairable because their technology will not become obsolete as easily. Shi et al. (2023) introduced a model for designing smart textiles, that considers the designed lifetime and level of technology in the textiles, which guides PD towards optimal resource use and the most environmentally friendly CE processes for the products. Bundgaard and Huulgaard (2019) found links between luxury general EEE products' characteristics and the CE, as the high expected quality and price of such products set demands for long-lasting repairable products with extended software support. The article also pointed out the slower development cycles of luxury products and the effort that designers make to ensure such products resist obsolescence.

Cole et al. (2019) studied the barriers to reusing general EEE and found that it was hindered by producer resistance, unsuitable infrastructure, and consumer attitudes and expectations, which affect the design of products. Limited spare part availability and repair information as well as limited availability of software updates were found to hinder CE compatibility. Yamamoto & Murakami (2022), Sahajwalla & Hossain (2023) and Williams & Shittu (2022) found, that more durable products and modular upgradeability were needed to reduce the risk of obsolescence, and thus help with reusability.

Coughian et al. (2018) studied the feasibility of repurposing EOL notebook computer parts as thin client computers and found the practice feasible but limited by issues with disassembly and motherboard design which did not promote their reuse in new applications. This, again, points out the importance of disassemblability. Mugge et al. (2018) studied customers' evaluations of the effect of visual and verbal information on the prior use of refurbished general EEE. They found that customers have a complex relationship with the signs of wear seen on used products and concluded that the design of a product has an important role in making refurbished electronics attractive to customers, that is, products that are designed to stay attractive to clients even when they are worn can enhance their compatibility to refurbishing.

3.1.2. *White goods*

Repair was a prevalent subject among white goods, appearing in four of the five articles considering this product group (Fig. 6). The results of the study shows issues in the repairability of these products concerned problems in fault diagnosis (Pozo Acros et al., 2020), lack of standardization (Tecchio et al., 2017), confusion about metrics to reliably assess repairability (Bracquené et al., 2021), and the unused potential in assessing component failure rates in printed circuit boards (Karagiannopoulos et al., 2022). Thus, the issues concerning repair are more about the information needed for repair rather the product not being suitable for it. Modeling the failure rate of discrete components was also suggested as a way to optimize the ecodesign of products (Karagiannopoulos et al., 2022). Neglecting regular maintenance was also recognized as a potential issue that could be remedied through PD which encompassed design for repairability and devices that notify users about maintenance (Pozo Acros et al., 2020).

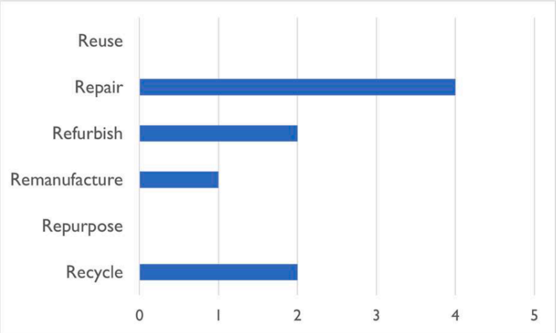

Fig. 6. Frequency of CE processes addressed in the white goods product group.

Refurbishing was addressed in two of the five articles, which found that mature technologies, which can be found in white goods, can be effectively designed to be robust and keep their functional and resale value for longer than less robust alternatives (Bakker et al., 2014; Bracquené et al., 2021a). Bakker et al. (2014) also addressed the topic of remanufacturing white goods, which was found to be a less likely solution than other ways of prolonging their usable life as white goods already have a long planned lifespan. This further enforces the findings in the general EEE section about the dissonance between CE processes needs in PD.

3.1.3. *Industrial EEE*

The most common concern within this product group was the poor recyclability of materials, which was discussed in all the papers in this category (Fig. 7). The difficulty of disassembly was discussed in all papers in this category except for Mulvaney et al. (2021) and Jerome et al. (2023). Products such as wind turbine blades and photovoltaic systems are relatively maintenance-free during their usable lifespan but ultimately create large amounts of waste that is difficult to reuse or recycle. Sahajwalla & Hossain (2023) argue for the optimization of critical material use, disassemblability, and modularity to create products that resist obsolescence and enable lifetime extension. However, Norgren et al. (2020) pointed out that the desire to decrease critical raw material concentrations in products could lead to their recycling becoming less effective. This brings up an interesting issue with critical raw material use and CE, namely that the optimization of material use can have negative effects on their potential in CE. Similarly, Singh et al. (2021) found that the most effective way to reduce the environmental effect of photovoltaics was to design them for a longer usable lifespan so less material is introduced into the product stream in the first place and less waste will be generated. Similarly, Jerome et al. (2023) points out, that with large high voltage electric motors the environmental gain from repair can be insufficient compared to the efficiency gain of new, more efficient motors, and design should focus on creating motors that work efficiently for a prolonged time. Mulvaney et al. (2021) also recognize the complexity of the issue, pointing out that "*Sometimes what seems*

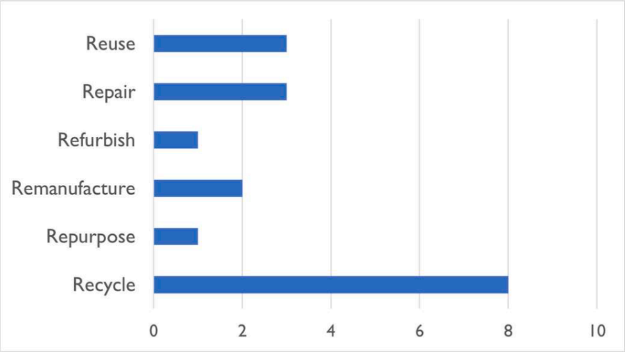

Fig. 7. Frequency of CE processes addressed in the industrial EEE product group.

intuitive, does more environmental harm than good illustrating the need to evaluate material impacts by LCA (life cycle analysis) or by contextualizing critical aspects such as environmental justice." Again, like in general EEE and white goods, analysis of the material shows competing interests with designing for different CE processes.

Conti & Ocrioni (2020) recognized the positive effect of reusing electrical components as early failure rate can be lower in reused components providing that the use history of the component is known and traceable. Technological and functional obsolescence was recognized as an issue with industrial mechatronics in Chouinard et al. (2019), who found that, as with white goods, easing remanufacturing would aid in the circularity of products with rapidly developing technologies. This study also found that the lack of extended software support affects the circularity of products in this product group. Alkouh et al. (2023) suggest a index of repairability as a tool to assess the repairability of industrial EEE, which takes into account the design of the product and the availability of spare parts, documentation and software support.

3.1.4. Batteries

All articles about batteries found problems in the current battery design concerning circularity. Issues with recycling were addressed most often in this product group, being discussed in 10 of the 13 articles about batteries (Fig. 8). The articles discussing the recycling of lithium batteries were mostly concerned with the valuable critical raw materials found in the battery cathodes, which are hard to extract. As Ferrara et al. (2021) explained in relation to the challenges of directly recycling cathodes for reconditioning and reuse: *"Indeed, current batteries are not designed to be opened, and partial disassembly and subsequent reassembly are not possible without compromising their functional state."* In line with these findings, design for disassembly was suggested in relation to all the other discussed CE processes except repurposing to aid in the effective reuse and recycling of batteries (Albertsen et al., 2021; Norgren et al., 2020; Talens Peiró et al., 2017; Thompson et al., 2021). Lander et al. (2023) found, that disassemblability costs can vary up to 75 % between different battery designs, with features hindering disassembly, such as structural adhesive use and complex design slowing down and complicating the process. Lampón (2023) suggests reducing the number of components to aid in disassemblability, while Akasapu & Hehenberger (2023) suggest a conceptual design model with decision points, where the desired specifications of the battery guide towards optimal battery pack design for CE. Developing more effective battery health diagnostics was also recognized as an important step in ensuring a more effective CE of batteries, especially in repurposing and reusing them (Albertsen et al., 2021; Ferrara et al., 2021).

It was also found that batteries are not currently designed for repurposing (Albertsen et al., 2021; Canals Casals et al., 2019), the regulatory framework does not encourage the CE of large batteries (Ahuja et al., 2020), and there are conflicting interests even in regulatory incentives concerning the reuse or recycling of batteries, as recycled materials are incentivized more generously than different reuse options (Albertsen et al., 2021). The risks involved in handling lithium batteries have imposed limits on how they can be transported, making the logistics of their circular use difficult (Mulvaney et al., 2021). Thompson et al. (2021) point out that reducing the concentration of critical raw materials has a negative effect on the viability of recycling lithium batteries, which is in line with the findings of Norgren et al. (2020) mentioned in the industrial EEE section. As with all the other product groups, competing needs between CE processes can be found with batteries as well.

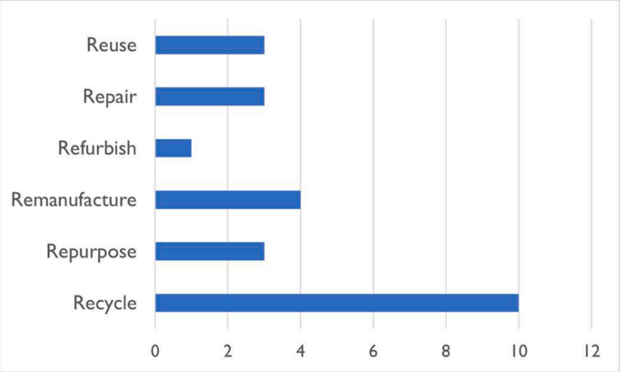

Fig. 8. Frequency of CE processes addressed in the batteries product group.

As potential remedies for these issues, Huster et al. (2022) simulated the potential of remanufactured EV batteries in the UK market and concluded that there is a market for remanufactured batteries even if their lifespan outlasts that of the vehicles they are originally installed to. Canals Casals et al. (2019), on the other hand, finds the current design of batteries not suitable for reuse and argues for the servitization of EV batteries as a driver for their eco-design.

3.2. Synthesis of results

Fig. 9 presents the four selected product groups and studied CE processes, showing the total number of times CE processes were addressed in the collected material. The four selected product groups all revealed an emphasis on recycling, which was the most prevalent CE process in all groups except for white goods. Recycling issues consisted of the unprofitable nature of liberating materials for second use, regulatory difficulties, and disassembly difficulties.

The theme of difficulties in disassembly was also repeated across product types and CE processes. Disassemblability seems to be a key function in enabling the CE of general EEE products, as any attempts to prolong the usable life of products or liberate materials of interest seem to run into related issues. These issues can be technical, as in the difficulty of disassembling a product without causing damage to it or related to the availability of proprietary tools and information needed for them. Another recurring theme was the competing interests between different CE processes – designing a product to be utilized in the CE in a certain process seems to decrease its ability to be utilized in another one. Table 5 provides a summary of key results by product group.

Furthermore, research gaps were identified in the review. Refurbishing and repurposing were significantly outnumbered by the other CE processes addressed in the studies included in the sample, being addressed by under 15 % of the selected articles. Furthermore, certain CE processes were more prominently addressed in some product groups than in others. For example, remanufacturing was little addressed in the industrial EEE and white goods product groups.

4. Discussion

This paper reviewed the current literature to identify the limiting factors to CE in the PD of EEE and the measures that can be taken to improve its status. The target was also to elaborate on the entropy-based hierarchy of CE processes (King et al., 2006) to advance the CE of EEE. A systematic literature review was used to study current literature, which resulted in 44 peer-reviewed scientific articles being categorized and studied. The articles were categorized based on the CE processes they addressed, and the types of products studied.

Regarding PD challenges hindering the CE of EEE, the first key finding is that a common thread exists among the material showing that issues with recyclability of products is prevalent in the area. Only in one product group, white goods, it was not the most commonly addressed CE process. Even though recycling is the least preferable option from a material preservation point of view of all the CE processes, it is almost certainly the end point for all products. Thus, the results of this study confirm that recyclability should be a design consideration regardless of product type. However, the prevalence of recycling issues in the collected material points out research gaps on less prevalent themes, for

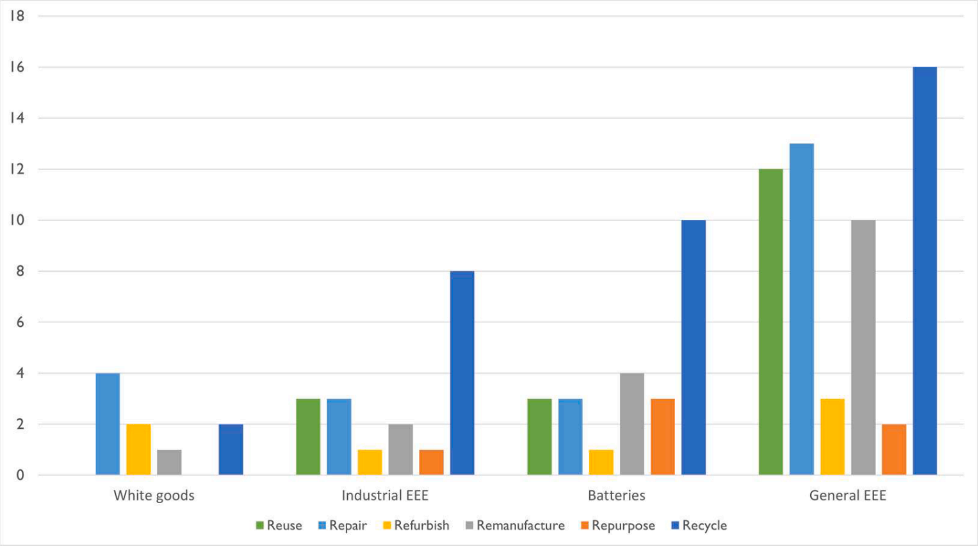

Fig. 9. Frequency of CE processes addressed in articles per product group.

Table 5
Summary of key results.

Product type	Key product design issues	Proposed solutions	Issues common to all product types
General EEE	Poor disassemblablity Issues with liberating materials of interest when recycling PD that does not encourage CE Lack of standardization in CE goals and metrics Customer attitudes towards circular products	Design for disassembly Product family approach to PD Resisting technological obsolescence through PD Designing products to withstand wear	Poor disassemblablity Poor recyclability Design trade-offs between CE processes **Solutions common to all product types** Design for disassembly Design for recyclability Focused PD goals to alleviate the effect of trade-offs between CE processes
White goods	Poor disassemblablity Issues with fault diagnosis Lack of standardization	Design for disassembly Design for repairability Component failure rate modeling	
Industrial EEE	Large amounts of waste that are difficult to recycle Poor disassemblablity	Design for disassembly Designing for longer product life Designing products to resist technological and functional obsolescence	
Batteries	Poor disassemblablity Insufficient battery health diagnostics for reuse and repurposing Regulatory barriers	Design for disassembly Creating better battery health diagnostics Facilitating the CE of batteries through business models (e.g., servitization)	

example refurbishing and repurposing, which were the least addressed processes in the material analyzed in this study. Certain topics are visible in all selected product groups and relevant to many CE processes. Most notably, issues with disassembly were noted in all product groups and across CE processes. Thus, another important finding in this study is that design for disassembly can be considered a key enabler of CE for the studied product groups. This finding is in line with previous literature on the subject (e.g. Talens Peiró et al., 2017; Vanegas et al., 2018) and implies that further improvements on the matter are required to effectively implement the CE of EEE.

Considering themes outside recycling and disassembly, the results are more diversified, but a clear theme arises from tension between different CE processes: designing for one can have negative effects on another. Thus, designing for CE needs to be systematic about the way products will be utilized in the CE. Furthermore, the type of product addressed starts to have a greater effect on the discussed circular utilization of products in themes outside recycling and disassembly. Articles on products in the general EEE category consider CE processes for lengthening the usable life of products, such as smartphones, with a few usable years (e.g. Atlason et al., 2017; Cordella et al., 2021; Mugge et al., 2018), whereas those in the white goods and batteries categories target longer lifespans (e.g. Bakker et al., 2014; Bracquené et al., 2021; Huster et al., 2022). What seems to emerge as a common theme is that the technical maturity of a product or its components is directly connected to the recommended best practices in the literature: The less mature the technology, the more energy intensive CE process is needed. For example, a high-tech product with cutting-edge technology is not expected to withstand the technological development of the future and meet the requirements of newer software made possible by more powerful available hardware. Thus, it is expected that non-mature technologies will evolve quickly, and it is important to design products that can be effectively used in the CE by being able to adapt to emerging developments in technology through, for example, remanufacturing and utilizing the materials invested in them by recycling at EOL. In the same fashion, the more mature the technology, the less desirable it is to alter the product in order to utilize it in a circular way. This finding implies the use of less-intensive CE processes such as reusing or repairing and for products with mature technology. Thus, we propose that:

Proposition 1: Technologically mature EEE or its components are suited for low-energy CE processes, such as reusing and repairing, while those with lower technological maturity are better suited for more energy-intensive CE processes, such recycling.

Comparing this to the entropy-derived model of self-replenishing loops, where the energy needed for reusing, repairing, remanufacturing, or recycling were compared and ranked accordingly (King et al., 2006), design priority considerations can be mapped out according to the technical maturity and expected lifespan to the minimum entropy PD priority model introduced in Fig. 10.

The minimum entropy design priority model suggests applicable CE processes for products, components, or assemblies based on their expected lifespan and technological maturity. The model considers the connection between technological maturity and the priority of applicable CE processes and combines it with previous literature and CE goals. In the minimum entropy PD model, the CE processes mentioned in this study are ranked from most entropy-inducing to least entropy-inducing – from recycling to reuse (Potting et al., 2017) – with an arrow pointing towards preferable, low entropy processes. The vertical axis represents the technical maturity of the product, assembly, or component, i.e., the level of technological development expected in this area during the expected lifespan (e.g., Nolte, 2008, pp. 7–17). This lifespan-expectancy is depicted on the horizontal axis, which depicts the length of time that the product will be expected to be used before EOL including changes in its lifecycle – i.e., ending of its primary lifecycle and starting of subsequent lifecycles as per CE principles. This is not rigidly defined in years, but a product that is expected to last for a maximum of a few years is considered to have a short lifespan. At the other end of the spectrum, products that last for up to 20–30 years can be considered to have a long lifespan in the context of EEE. The positioning of a product in this graph shows the CE process that enables the CE of the product with the least possible invested energy without sacrificing the possibility of technological development. The shape of the heat map is based on the assumption that the less mature a technology is and the shorter its lifespan, the more energy is needed to utilize it in the CE. The model also considers the basic principle of lengthening the usable lifespan of products in CE, which is why a short lifespan increases entropy more substantially than lower technological maturity. Thus, products with high technological maturity and a long lifespan are at the least entropy-inducing end of the model. This implies that products such as photovoltaics, that have a long-expected lifespan and are not expected to be replaced with new technologies during their intended usable lifespan, should be designed for reuse. At the other end of the spectrum, short-lifespan products with new technologies require more entropy-inducing processes, such as recycling, to be utilized in the CE. It is also worth noting that the CE processes are not mutually exclusive but designing for one CE process can negatively affect the compatibility on other processes. For example, a product can be simultaneously repairable and remanufacturable, but these attributes can negatively affect product reliability. All products should naturally be recyclable after their lifespan cannot be extended further. This leads to the second proposition of this study:

Proposition 2: Technological maturity and expected lifespan are indicators of suitable CE processes for product design, as described in the minimum entropy design priority model.

5. Conclusions

This study conducted a systematic literature review to analyze PD-related issues within the circular economy of EEE. The introduced minimum entropy design priority model is the key contribution of this study, and it is a generalization based on the findings of the conducted systematic literature review. Together with the previous findings of the need for products which are designed for disassembly and recycling, the presented minimum entropy PD model provides a framework for product designers and manufacturers to develop EEE that meet the requirements of the CE. The developed model can also provide valuable ideas for policymakers, legislators, and regulators. However, this model is derived from the confines of this study and should be further refined with case examples from relevant industries. This is also linked to the limitations of this study – the systematic literature review identified a large number of studies that were narrowed down with strict filters and exclusion and inclusion criteria to achieve the final sample of articles. This method allowed to find articles that communicate the state of the CE of EEE on a broad scale, but a review of more focused studies on certain CE processes would naturally yield more specific results about those processes. As such, the proposed minimum entropy design priority model should be seen as a generalization based on the used source material – not as a definite model for all EEE. Further research should also be conducted to compare the introduced model to CE business models utilizing the discussed CE processes to see if there are opportunities or limitations in utilizing this model in the PD of EEE. In addition, the contradictions found between the design goals for different CE processes should be studied further to achieve optimal sustainability. Indeed, this study accounts for such tensions between environmentally optimal production and the total environmental impact of products only

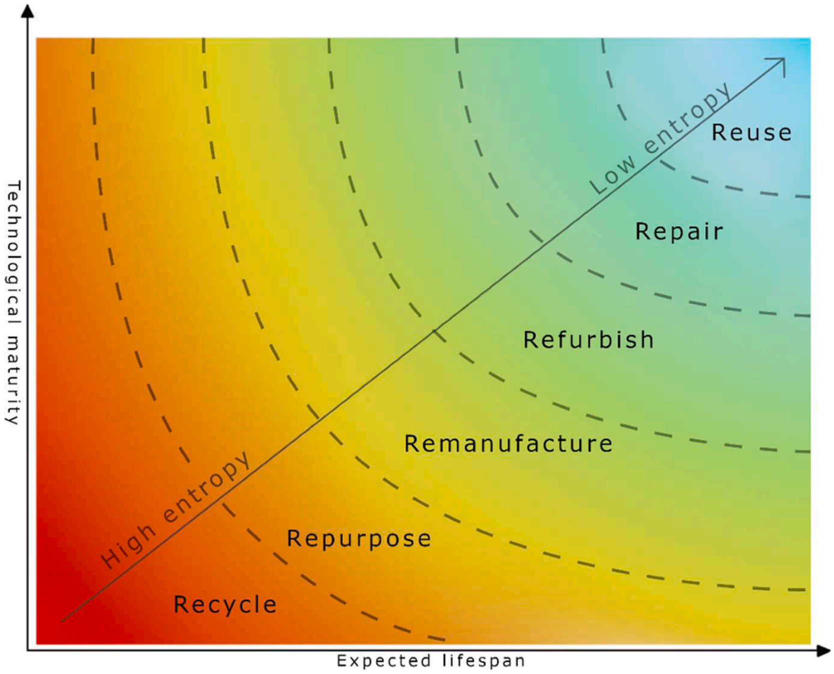

Fig. 10. Minimum entropy PD priority model and the related CE processes.

in the magnitude that they appear in the studied literature, and further research should be conducted to find other possible conflicts and trade-offs between design goals aiming for sustainability and circularity. Also, the low number of studies found on the effect of PD on the CE in some areas indicates that several research gaps still exist. The less studied areas include the remanufacturing of industrial EEE and white goods as well as refurbishing.

CRediT authorship contribution statement

Juhoantti Köpman: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation. **Jukka Majava:** Writing – review & editing, Validation, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The authors acknowledge funding from the University of Oulu & The Research Council of Finland Profi5 326291.

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