Extended Abstract
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Life cycle assessment (LCA) of remanufactured electrical and electronic products; a review of methodological choices

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Introduction

Electrical and Electronic Equipment (EEE) is widely recognized for its substantial environmental impact, containing numerous toxic substances and contributes significantly to energy consumption in manufacturing and waste generation. This waste production is often driven by the continuous evolution of EEE in terms of new features and marketing strategies employed by companies to promote the perception that consumers must upgrade frequently to remain current, leading to premature obsolescence and shortened device lifespans (Neto and Bloemhof, 2009; Yuksek et al., 2023).

Circular economy (CE) approaches have emerged as essential strategies to address these pressing environmental issues (Ada, 2021; Androniceanu, 2021). Within the CE framework, remanufacturing has gained prominence due to its potential to mitigate the environmental impacts associated with excess production of electronic equipment through product lifetime extension (Alkouh et al., 2023).

Remanufacturing involves restoring a used product to meet or exceed its original performance specifications and user expectations, accompanied by a warranty comparable to that of a newly manufactured product. The process includes multiple stages: collection, initial inspection and sorting, dismantling, cleaning, replacement of damaged parts, reassembly, upgrading, installation, and final testing (Gan et al., 2018).

To better understand the environmental advantages of product lifetime extension strategies like remanufacturing, it is crucial to evaluate environmental impacts through comprehensive assessment tools such as Life Cycle Assessment (LCA). LCA quantifies the environmental impacts of a product or service throughout its entire life cycle. By analyzing each stage, LCA helps identify areas where environmental burdens can be reduced, supports informed decision-making for product design improvements, and facilitates the comparison of different strategies aimed at extending product lifespan (Curran, 2015).

However, the LCA of remanufactured products remains a subject of debate, as the modelling choices used can significantly influence the results (Peters, 2016; Suhariyanto et al., 2017; Mann et al., 2022). Existing literature highlights a notable gap in research on this topic, particularly for EEE. To the best of our knowledge, our study is the first to critically review LCA studies based on remanufactured EEE.

This paper presents a literature review of studies on LCA of remanufactured EEE. The studies were analysed regarding the methodological aspects of LCA i.e. functional unit, system boundary, allocation method, inventory data, along with their results. It was examined whether they have provided a clear description of these and how these decisions influenced the LCA and its outcome. The results regarding the environmental impact of remanufactured EEE along with rebound effects were also analysed and reported. Additionally, recommendations were provided for future studies on LCA of remanufactured EEE.

Methodology

The literature review was conducted through an extensive search in scientific databases, specifically Scopus and Google Scholar for studies published between January 2000 and

November 2024. The search used the terms and their variants, “life cycle assessment” and “remanufacturing”, yielding a total of 166 results. These initial findings were rigorously screened to include only research papers that explicitly addressed remanufacturing at the end-of-life stage, while excluding studies that focused on other end-of-life strategies such as refurbishment and recycling.

The screening and selection process was performed following the Preferred Reporting Items of Systematic reviews and Meta-Analyses (PRISMA) as shown in figure 1.

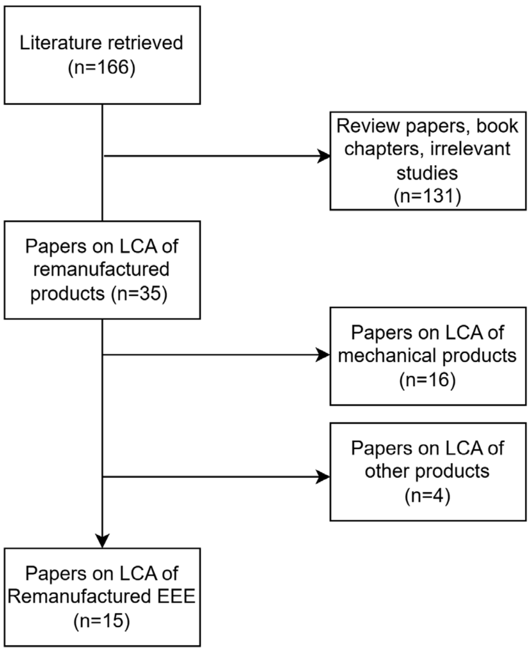

Figure 1. The screening approach of literature.

The literature review process identified 35 articles of LCA of remanufactured products. Of the 35, 16 articles pertained to mechanical products while 4 referred to other sectors, these were considered out of scope of this assessment. Finally, 15 articles on EEE were identified as the focus of the literature review in this study.

According to ISO 14044: 2006, it is crucial for LCAs to clearly state the goal and scope, functional unit, system boundary, inventory data, allocation and impact assessment method. Thus, these methodological aspects in the different LCAs were assessed.

Results and Discussion

The review of LCA studies on electrical and electronic equipment (EEE) showed that out of 15 studies, six did not clearly report key methodological aspects, such as the functional unit, system boundary, and allocation methods. Most studies relied on secondary or mixed data, particularly in the use phase, while few utilized primary data. Attributional modelling was employed in all studies except Wrålsen and O’Born (2023), which adopted a consequential approach.

The products reviewed for this study are mentioned in table 1. Electric bicycle motor, sparkplug and electrophysiology catheters are considered as electric products because they rely on electricity to perform their core functions.

	Product(s)	**Authors**
1	Laptop	Yuksek et al. (2023)
2	Computer	Fatimah & Biswas (2016)
3	Computer	Mann et al. (2022)
4	Phone	Neto and Bloemhof (2009)
5	Phone	Pamminger et al. (2021)
6	Phone and Refrigerator	Lu et al. (2017)
7	Portable power station	Yang S et al. (2024)
8	Li-ion battery	Wrålsen and O’Born (2023)
9	Electro-physiology catheters	Schulte et al. (2021)
10	Telecom equipment	Goldey et al. (2010)
11	Photocopier	Kerr and Ryan (2001)
12	Electric bicycle motor	Grosse Erdmann et al. (2023)
13	Sparkplug	Zhuang et al. (2023)
14	Li-ion battery	Yang H et al. (2024)
15	Coffee machine	Nikolic et al. (2024)

Table 1. Products and their corresponding authors of reviewed literature.

When assessing the environmental impacts of a product, it is essential to rely on accurate assumptions of its use. A product may have a higher environmental cost during manufacturing, but could compensate for this by offering significant energy savings during its operational life. However, if the use phase assumptions are incorrect or too generalized, it can lead to inaccurate assessments (Sassanelli et al., 2020; Curran 2015).

All studies reviewed, except Lu et al. (2017) which assessed an obsolete refrigerator, reported that remanufacturing led to a significant reduction in GHG emissions, resource use, and energy consumption compared to conventional manufacturing. For instance, Yuksek et al. (2023) presented that the remanufacturing scenario resulted in 21 kg CO_2eq compared to 331 kg CO_2eq for conventional laptop manufacture through use of primary data.

A key challenge in LCA of remanufacturing is the allocation problem, typically addressed through either the cut-off approach or system expansion approach. Both methods comply with ISO 14044 standards, with the cut-off approach representing a "supporter" perspective and system expansion approach a "neutral" perspective on remanufacturing, as noted by Peters (2016). Most studies used the cut-off or supportive approach. Lastly, only as Wrålsen and O'Born (2023) and Neto and Bloemhof (2009) explored the potential rebound effects associated with remanufacturing.

The review offers several important recommendations to strengthen the rigour and depth of LCA in remanufacturing EEE. Key among these is the thorough application of established LCA standards to ensure transparency and reproducibility, allowing researchers to clearly specify and justify their methodological choices. Additionally, incorporating both supportive and neutral perspectives on remanufacturing either within the LCA or via sensitivity analysis can highlight how varying assumptions impact results, offering a more nuanced view of remanufacturing's effects.

The review also emphasizes the need for primary data, especially in the use phase, to reduce uncertainties associated with secondary data and enhance the precision of findings. Finally, it highlights the importance of addressing rebound effects, where resource efficiency gains may lead to increased consumption, thereby impacting the overall environmental benefits of remanufacturing.

Conclusions

The review highlights a pressing need for greater transparency and consistency in reporting functional units, system boundaries, inventory and allocation methods in LCA studies of remanufactured EEE. These methodological choices impact and influence LCA results, making clear and consistent reporting essential. The review also suggests that remanufacturing may offer substantial environmental benefits for EEE. Additionally, the recommendations provided aim to enhance the relevance and robustness of LCA findings for informed sustainability decision-making.

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