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RESEARCH

Analysis about the incorporation of remanufacturing concept into life cycle assessment theories

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Abstract
In Circular Economy, remanufacturing is one of the most beneficial circular loops to guarantee the conservation of resources. There are some alternatives to multiple life cycle products such as reuse, renovation, refurbishment or recycling although remanufacturing is the only option that introduces multiple life cycle products in the market as if these products were new. The objective of this research is to assess the requirement of a better alternative for the End of Cycle in Life Cycle Assessment from the remanufacturing perspective. Life Cycle Assessment is an environmental accounting and management approach that considers all the aspects of resource use and environmental releases associated with an industrial system from cradle to grave. Aiming at this, different system boundaries and allocation methodologies have been considered. The following four methodologies have been analyzed: Ecoinvent, Environdec, International Reference Life Cycle Data and European Product Environmental Footprint. In the studied methods, the recovery appears as reuse, energetic recovery or recovery to second life. These methods elude the remanufacturing perspective; therefore, how remanufacturing would fit for each of the selected methodologies has been analyzed.

Keywords Life cycle assessment · Circular economy · Remanufacturing · Ecodesign · End of life

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Introduction

The world is currently using the equivalent of 1.7 planets to support human activities. This is an unsustainable rate at today's levels of consumption [1]. The manufacturing industry is a major consumer of the material and energy resources generating significant amount of waste [2]; therefore, resource recovery is considered to be one of the important aspects of waste managements [3]. Developed economies are therefore committed to promote the so-called Circular Economy (CE) as our common necessary future.

According to the European Commission (EC), CE starts at the very beginning of a product's life [4]. Throughout a product's life, the design phase and the production processes have an impact on sourcing, resource use and waste generation [5].

Remanufacturing is one of the most beneficial circular loops to ensure the conservation of resources. In general, the environmental benefits of remanufacturing are embedded in the delay of disposal, the alleviation in resources in resources depleting and the savings in embodied energy to make new products [6], whereas in the material recycling case the materials used in manufacturing are salvaged, but not the embodiment energy used to make the parts and assemble them together. This embodiment energy is salvaged when performing remanufacturing.

There are other options to multiple life cycle products (MLP) such as reuse, renovation, refurbishment or recycling. Despite this, remanufacturing is the only option that introduces MLP in the market as if these products were new. These remanufactured products could have the same guarantee as a newly manufactured product [7].

Ecodesign defines a way to develop products in which environmental aspects are given the same status as functionality, durability, costs, time-to-market, aesthetics, ergonomics and quality. Ecodesign aims at improving the product's environmental performance and may be seen as a way to develop products in line with the concept of sustainable development. From another point of view, ecodesign is a proactive management approach that directs product development towards environmental impact reductions throughout its life cycle. [8]

Life Cycle Assessment (LCA) is an environmental accounting and management approach that considers all the aspects of resource use and environmental releases associated with an industrial system from cradle to grave. [9] LCA methodology is one of the most useful methodologies to ecodesign and to perform environmental assessments of products and services.

This LCA procedure is specified in the ISO 14040 standard [10]. This methodology can provide quantitative information to enable better choices leading to a more sustainable planet and society. The purpose of this research is to assess the requirement of a better alternative for the End of Life (EoL) in Life Cycle Assessmen from the remanufacturing perspectivet. With this aim, different system boundaries and allocation methodologies were studied. The following methodologies have been analyzed: Ecoinvent, Environdec, International Reference Life Cycle Data (ILCD) and European Product Environmental Footprint (PEF).

This paper is structured as follows. Firstly, it presents the context of CE, ecodesign and remanufacturing. Secondly, section 3 presents a selection of the methods and general approach to comparison. Thirdly, Section 4 presents the methodologies analyzed. Finally, the remanufacturing approaches for LCA definitions are in Section 5.

Context of CE, remanufacturing and LCA

The hierarchies adopted by the EU in 2008/98/EC directive establishes waste policies from a CE approach. In Table 1 we can see the design for circular loops [11, 12].

The closed-loop product systems usually include recycling, remanufacturing or reuse as EoL management strategies, applied at the end of the useful life of products. Since they aim at extending the life of products, (or their components) conserving materials, energy and environment, reuse and remanufacturing are the preferred EoL management strategies [2].

Theoretically, a circular product must be prepared to be reformulated infinite times. To achieve this, it is important to know the best option for each part of the products. In order to decide on the best options, a good diagnosis and a design improvement are essential. To solve these issues, design strategies should focus on material efficiency, extension of the product's life and the recycling [9, 13].

According to the EC's adjustment, and in order to minimize leakage of resources through landfills or energy recovery, closed-loop product systems should be based on maintenance, reuse/redistribution, renovation/remanufacturing and recycling [3, 14]. Figure 2 shows an adaptation of EC waste hierarchy (Fig. 1) [10].

It is essential to distinguish the different processes that may take place within CE [3]:

1. Repair (repair defects but without guarantee),
2. Re-use (re-use without modification),
3. Renovation (aesthetic improvement with limited functionality improvement),
4. Reconditioning (possible adjustment for the item to get back to work again),
5. Recycling (extraction of raw materials to use them in new products), and
6. Remanufacturing (series of manufacturing steps that perform on the EoL of a product to produce new, better and protected products).

All the concepts explained above result in the following natural logic of return-recovery:

- Consumer return ➔ repair/reuse
- End of use return ➔ remanufacturing
- EoL return ➔ recycling

The great complexity involved in the circularity of a product must be taken into account. Nonetheless, it is important to know beforehand to what extent each product can achieve this circularity. This implies knowing which of the options is more sustainable for the company.

Table 1 A design strategies' hierarchy for product's life extension and recycling

Hierarchy	Definition (2008/98/EC)	Design Strategy
• Prevention	Measures taken to reduce the quantity of waste.	Material efficiency Longer product life
• Reuse	Using a product or component again for the same purpose for which it was conceived.	Product Repair Product refurbishment Product remanufacturing
• Recycling	Any recovery operation by which waste materials are reprocessed into the products, materials or substances whether for the original or for another purposes.	Product/material recycling

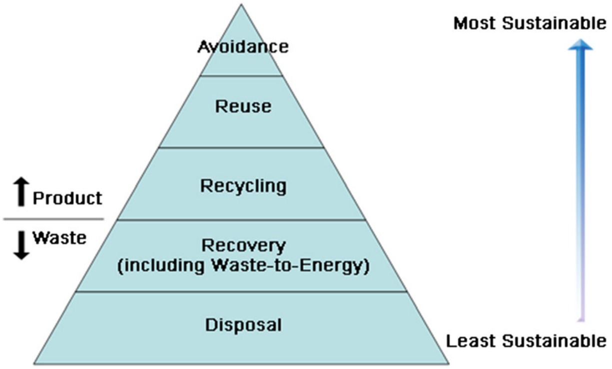

Fig. 1 Waste hierarchy of EC directive 2008/09/EC (Zunft & Fröhlig, 2009)

There are many differences between circular closures: for example, recycling will be more complex than reuse or the greater the closure is, the greater the complexity involved [2]. Figure 2 shows several circular closures.

LCA is an internationally standardized environmental assessment method. According to Kloepferr [15] the two most important features of LCA are the analysis from 'cradle-to grave' and the use of a functional unit for comparative studies. The international standards on this matter have been slightly modified for International Organization for Standardization (ISO) 14,040:2006 and ISO 14044:2006 superseded former ISO series 14,040 to 43 (1997–2000) [10, 16].

Due to the need to change form a former linear economy to the new reality (CE, Internet of Things, Industry 4.0., Additive Manufacturing and more innovations) [17] the complexity of LCA methodologies is increasing. Throughout the evolution of these methodologies, the approach to the bases and to the end of life has become more and more specific. Fist, recycling included in these methodologies. Later on, reuse was also included although a linear

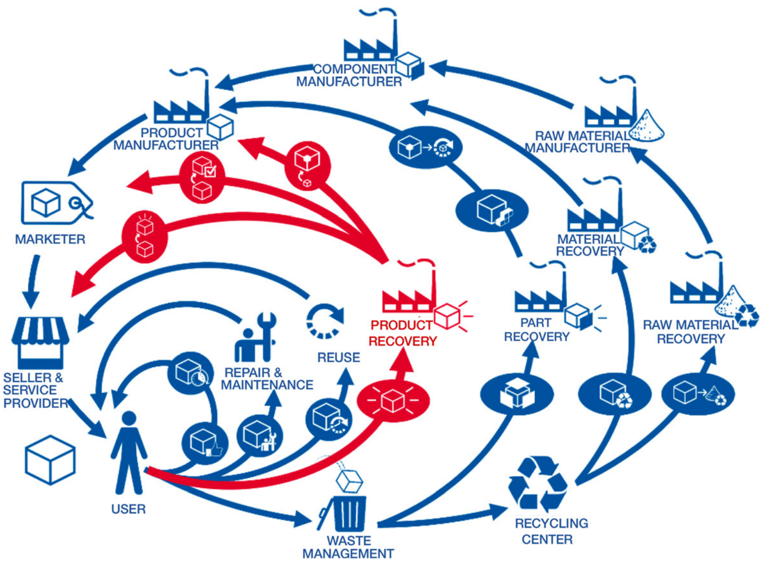

Fig. 2 Different cycle's closures, in red, product recovery references

perspective and a single cycle approach was kept. Both, marking the boundaries, together with establishing the allocation and avoiding a double counting between systems make LCAs more difficult and complex.

Four methodologies have been analyzed, three of them are already established in the market and the fourth one is undergoing a validation process. Besides, due to its increasing importance and recognition in the international scenario and to its complexity, the evolution and adaptability of the methodologies have been assessed from a remanufacturing approach.

Approaches of comparison of LCA methods

Our context to analyze the LCA methods have principally consisted of the allocation of EoL approach and system boundaries. For this study, it is essential to study the temporal evolution of the methodologies in order to understand their increasing complexity so as to adapt any of these methodologies to remanufacturing.

On the whole, ISO define allocation as "partitioning the input and/or output flows of a process to the product system under study". In the LCA Handbook, economic allocation is counseled as the baseline method for most allocation situations in a detailed LCA. Another option could be physical allocation. All of this is explained in the two-step ILCD allocation procedure [18].

Different allocation approaches related to recycled products were proposed by different researches such as the market-based approach [19] proposed by the EVR model of Vogtländer et al. [20] and a material-quality-based approach [21]. The ISO 14044:2006 standard for LCA describes this issue in a general, not in-depth way, and provides only a conceptual framework to guide designers in their EoL modeling processes [16, 22].

At the same time, there are examples of LCAs made with remanufactured products at the academic level. Nevertheless, there is no agreement regarding the setting of the system boundaries, let alone the comparison between a remanufactured product and a new one. According to the research by Sundin and Lee [6], there are five main variables when it comes to marking the system boundaries of the life cycle in a remanufacturing case. These are usually classified in the following five categories:

1. Comparing one manufacturing cycle with a remanufacturing cycle. The focus here is to compare strictly the difference in employing remanufacturing instead of manufacturing at the stage level. It does not include life cycle perspectives [23, 24].
2. Comparing the entire life cycle with remanufacturing (in this case replacing the manufacturing stage but including the take backstage). This means a comparison between two full life cycles- one as the normal product life cycle and the other with the manufacturing stage being replaced with remanufacturing or recycling with the inclusion of the take back stage [25–28]
3. Comparing one manufacturing cycle with a remanufacturing cycle and a recycling cycle. Here, two end-of-life strategies are compared with one manufacturing cycle to see if remanufacturing is indeed more environmentally preferable [29].
4. Comparing one life cycle with manufacturing + one life cycle with remanufacturing with two life cycles with manufacturing. It must be taken into account that at least one new cycle of manufacturing is necessary before a remanufacturing cycle is possible [30].
5. Comparing the different number of times that the products are being remanufactured [31].

Therefore, due to study differences, it is necessary to regulate and lay a solid foundation for performing the LCA of a remanufactured product.

Our analysis takes into consideration four methods that constitute an internationally recognized representative sample in LCA assessment. These methods are: Ecoinvent, Environdec, ILCD and PEF. This selection was made following these criteria: Ecoinvent as the most used LCA database; Environdec as the company responsible for environmental product declarations (EPD); and ILCD and EC PEF refer to formulas and methodologies developed by the Joint Research Centre of the European Commission (JRC).

LCA methods

Ecoinvent (2003)

The Ecoinvent database has three allocation systems:

- Allocation, Recycled Content or Cut Off
- Allocation, At the Point of Substitution (APOS)
- Consequential

The first one, the cut off system model, has the effect that recyclable materials are cut off at the beginning of the treatment processes, becoming available and burden-free for subsequent uses. In this case, if a material is recycled, the primary producer does not receive any credit for the supplying recycled materials. The consequences are that the materials are available and free of environmental burden for the recycling processes and the secondary materials (the recycled ones). In this case, the environmental burden is only borne by the recycling processes. In addition, producers of waste do not receive any credit for the recycling of products resulting from any waste treatment [32].

The second one, the "Allocation, APOS" system model contains two methodological options:

- Using the average supply of product offers, as described in the market activity datasets; and
- Using division (assignment) to convert multiproduct datasets to single product datasets.

The flows are allocated in relation to their real value, which is the corrected economic income by gaps imperfections and market fluctuations [33].

The third one, the "consequential" system model addressed the methodological options mentioned in APOS, with the following differences:

- Using unrestricted product offers, based on data sets of market activity, as well as information included in the technological level; and
- Using substitution (system expansion) to convert multiproduct data sets into a single product.

The "consequential" system model is a model to reflect the consequences of small–scale decisions on the long-term, taking into account the restrictions that are applicable to this scale and the time horizon. This consequential system considers long-term changes and the rule for the technological level of unrestricted suppliers depending on the market trend.

Table 2 shows the principles of the different options in Ecoinvent

Environdec (2008)

Environdec is the company that regulates the Environmental Product Declaration (EPD ®). An EPD ® is a verified and registered document that communicates transparent and comparable information about the environmental impact of products' life cycle. In the EPD ® system specific methodological choices regarding waste should be established. When the LCA is applied to solid waste management systems, a few issues should be considered: the upstream and downstream boundaries system, the recycling allocation, the multiple supplies allocation and the period time.

Waste, in its broadest sense, includes waste materials, used chemicals, sewage and worn products that are often subject to: incineration, waste or wastewater treatment, composting, deposition, recycling and reuse.

It is important to have a general allocation principle for each option:

- The environmental impact associated with the treatment of wastes not to be used by any subsequent user, rests on the waste generator. The waste is not considered a resource.
- The environmental impact of processing waste to transform it into a resource for subsequent user rests on the user of the resulting resource.

These principles defined in the Annex to the EPDs [34] have been established on the basis of the polluter-pays-principle (PPP).

Table 2 Principles of the different options in Ecoinvent

Ecoinvent	Principles
Allocation, Recycled Content. "Cut Off"	1- Primary production of materials is always allocated to the primary user of material 2- Recyclable materials are available burden-free to recycling processes and secondary (recycled) materials bear only the impact of recycling processes 3- Producers of waste do not receive any credit for the recycling or re-use
Allocation, Default	1- Two methodological options: 1.1- it uses the average supply or products, as described in market activity datasets 1.2- is uses partitioning (allocation) to convert multi-product datasets to single-product datasets 2- The flows are allocated relative to their "true value"
Consequential	1- The consequential systems model handless these two methodological choice differently: 1.1- it uses the unconstrained supply of products, based on market activity datasets as well as the included information on technology level 1.2- it uses substitution (system expansion) to convert multi-product datasets to single-product datasets 2- It reflects the consequences or small-scale, long-term decisions 3- Therefore a consequential model: 3.1- evaluates the changes 3.2- the substitution has important effects on the results of production with significant by-products 3.3- uses marginal provides 3.4- consumption of by-products creates demand for primary production

The PPP was adopted by the OECD16 in 1972 [5] as an economic principle to allocate the costs of pollution control. The following is the definition of PPP: *The "PPP allocation method" designates the responsibility to carry upcoming environmental impact for individual product systems and separates interlinked product systems at the pointing in the life cycle where they have their lowest market value resulting in a business-related approach regarding the differentiation of environmental impacts.*

The delimitation between two product systems is the point where the waste has its "lowest market value". This means that the waste generator must carry the full environmental impact until the point in the life cycle where the waste is transported to a landfill/scrap dealer or to the entrance of a waste treatment plant.

The subsequent user of the waste has to withstand the environmental impact of processing and refinement of the waste, but not the environmental impact caused in the "previous" life cycles. For example, in the case of re-use, the environmental impact of transportation of the used product for re-use by another party to some sort of collection site rests with the producer of the product, i.e. wastes that are re-used leave the product system without any environmental burdens. All environmental impact from there on is allocated to the re-user.

When deciding whether an input material flow is waste or a by-product, the weight that it has in revenue is considered as follows:

- If waste / by-products constitute a substantial part of the overall revenue of the waste generator, they should be considered as a by-product and some environmental impact should be assigned.
- If the waste / by-products do not constitute a substantial part of the total revenue of the waste generator, waste must be considered and treated according to the PPP method principles.

ILCD (2010)

The ILCD manual details the recycling process within the attributional model. The model is focused on recycling. However, other applications such as reuse or energetic valorization are not discarded. The assignation topic is included in the C annex, relative to "Modelling Reuse, Recycling and Energy Recovery" [18].

In the attributional model, some issues regarding recycling that arise are, among other, the following:

- Where to devise the limit of the system between the first life cycle and the later life cycles
- How to apply the ILCD two-stage assignment procedure to these cases

The following information will be required to answer these questions:

- Which is the market value (MV) of waste or products in the EoL?
- In the case of MV being less than zero, is there any valuable secondary good generated during treatment? And, if so, at what stage of processing?
- In any case, which are their physical characteristics and their MV?

There are two main cases, when the MV is less than zero and when the MV is greater than zero.

The waste product MV in EoL is greater than zero

From the point of view of the LCA, when the waste product MV is greater than zero at the point of waste's origin, it will be a co-product and the multifunction must be solved by allocation. This is done by applying the two-step procedure. As a special step, the process of the co- production must be identified: the process that has produced a product technically very similar to the waste product.

The two-step procedure is to apply the allocation when the MV of the waste product is greater than zero at its point of origin. This procedure is focused on two principles: physical causality and economical value.

The waste product MV in EoL is less than zero

In this case, the waste product cannot be sold directly, so it is not a co-product but a waste. There are two different cases:

- The first one is the case where no product of value is produced during the treatment process. In this case, all stages of waste treatment will be modeled and the entire inventory will be assigned to the first system than has generated the waste product.
- In the second case, a valuable product is generated during the treatment process. This secondary good is a co-product, so an allocation must be assigned.

The responsibility of the first system will finish when the product is achieving a MV of zero during the treatment process. Therefore, a load allocation to the secondary good is admitted at the stage where a valuable secondary good is produced.

The following procedure is applied. First, model the waste management processes until the waste crosses the "zero MV". Subsequently, the two–step allocation procedure will be applied at this point of the process.

PEF (2013)

The multifunction topic and their treatment in the recycling case are analyzed in EC in the 9 April 2013's Commission Recommendation "on the use of common methods to measure and communicate the life cycle environmental performance of products and organizations" [35].

In the situation of one or more energy reuse and recovery products, the multifunctional treatment of products is particularly complicated. These systems often become more complex.

Therefore, the Commission proposes a solution for the use of resources and emissions by the unit of analysis, which:

- It is applicable to open loop and closed loop recycling;
- The reuse of the evaluated product can be considered; this process is similar to that of recycling;
- The degradation cycle could be also considered. I.e., the quality differences between the secondary material (recycled or reused material) and the primary material (virgin material);
- Energy recovery could also be contemplated;
- The methodology allocates the impacts and benefits of recycling, in equal parts, on the one hand, to the producer using the material to be recycled and on the other, to the producer who recycles the material: 50/50 allocation.

Figure 3 reflects the System boundaries in a product's life n and the interaction between cycles bordering. [36]

Conclusions

Ecoinvent has three different allocation types (cut-off, At the Point of Substitution and consequential). Each allocation type has a different way to distribute environmental charges, although in all cases only the material recycled option is contemplated. If the point of substitution between cycles of a marketable material is analyzed, it can be established that this point of substitution is made by an economical allocation. The reuse or the remanufacturing of a product cannot be holistically incorporated in the Ecoinvent allocation modes. In any case, within a cradle to grave perspective, remanufacture could be applied in Ecoinvent if each remanufactured cycle is studied independently or if the changes in the remanufactured cycle are incorporated into the use phases of the LCA.

Environdec has more holistic perspective than Ecoinvent. Its principles are defined on the polluter-pays-principle. It defines that the subsequent user of the product has to assume the environmental impact processing and refinement of the waste, but not the environmental impact caused in the previous life cycle. In Environdec various options of EoL are analyzed, such as, waste

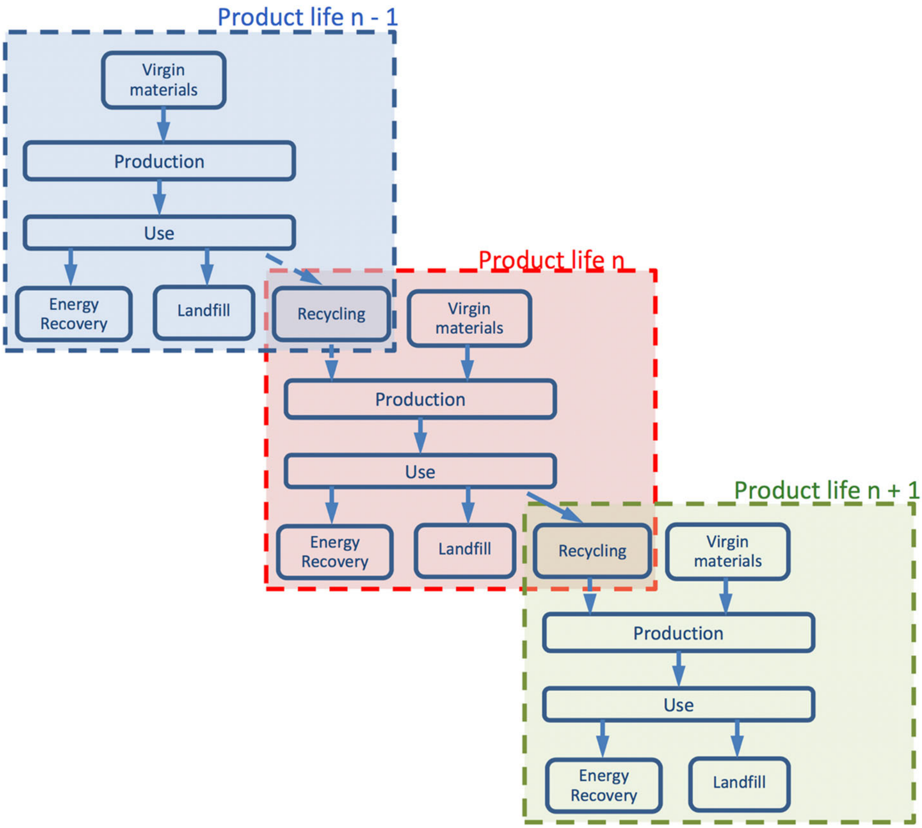

Fig. 3 System boundaries in product's life n and the interaction between cycles bordering

incineration, landfill, recycling and reuse. In reuse option the limit of first system is delimited until the transport of collection site. The environmental impact from that point is assigned to the re-user. Accordingly, the remanufactured product might be similar to the reuse option.

Two cases are distinguished in ILCD, when the MV is less than zero and when the MV is greater than zero. In our case, the product has a MV less than zero in it start point but as operations progress its MV exceeds the zero barrier. System limit is defined at the point where the value changes from negative to positive. The environmental impacts of that point are distributed in halves between the two cycles. Therefore, for a remanufactured product the turning point must be detected.

Finally, European Product Environmental Footprint proposes guidelines for the use of resources and emissions by the unit of analysis. Among the guidelines, the following can be outlined: the reuse of the evaluated product can be considered and this process is modeled similarly to a recycling one. In the case of recycling PEF defines that the impacts and benefits of recycling must be allocated in equal parts to the users of any cycle (50/50 allocation). Thus, for a remanufactured product, the environmental impacts from the time when the product is introduced in the factory until it leaves are distributed between cycles at 50%.

It can be concluded that if a product were analyzed in a LCA using these methodologies, the product would obtain different results depending on the methodologies and databases analyzed. This occurs because the limits of the system and the distribution of environmental loads are different according to the model used. This work will be followed by accomplishment of the LCA applying the different methodologies to some remanufactured products. The objective is to be able to choose the best option when defining the limits of the system and environmental loads to remanufactured products.

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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Affiliations

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