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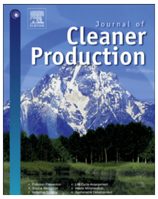

Accounting for the environmental benefits of remanufactured products: Method and application

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ABSTRACT

Although the importance of reusing products has been stated frequently, both in legislation and by academics, the scientific literature does not provide comprehensive and systematic methods of assessing the reuse of a generic product from an environmental point of view. Moreover, the definitions of reuse provided in the literature and legislation are not always consistent. This article introduces an original classification of different types of reuse, including some suggested definitions. It then focuses on remanufacturing, a type of reuse in which a used product (or its components) is returned to at least its original performance level. The article describes the development of a method for assessing, from a life-cycle perspective, the potential environmental benefits of remanufacturing energy-related products. The method includes several novel aspects: it helps to analyse possible trade-offs between potential environmental impacts and energy efficiency; it allows the independent modelling of some parameters that influence product reuse; and it can be applied even at the early stages of the design process, when some specifications may not yet have been defined. The environmental impacts of a product's life-cycle stages are used as input parameters for the assessment. The method is then applied to an enterprise server, a case-study product for which remanufacturing is a current market practice. A sensitivity analysis is included to check how uncertainties could affect the overall results. The results of the case study show that remanufactured servers, even those that are less energy efficient, can have lower environmental impacts than new ones. For example, reusing some components (e.g. hard disk drives and memory cards) is environmentally beneficial even if the remanufactured server consumes up to 7% more energy than a newly manufactured server. The case study also demonstrates how the method proposed could be used in the context of product policy discussions.

1. Introduction

The importance of reusing products as part of their end-of-life (EoL) process has been stated frequently, both in relation to legislation, for example in the European waste hierarchy (EU, 2008) and the Waste Electrical and Electronic Equipment (WEEE) Directive (EU, 2012), and by the scientific community (Graedel and Allenby, 1995; Lindahl et al., 2006). Remanufacturing is a type of reuse usually performed by industrial operators. According to Cooper and Gutowski (2015), Lund (1984) provided one of the first definitions of remanufacturing, describing it as an industrial process during which worn-out products are restored to a like-new condition by deconstructing/disassembling the product, cleaning and refurbishing any usable components, and reassembling the product with any new parts, if required. By reusing a product, it retains a higher value than if it were recycled (Nederland Circulair, 2015). Partially or fully reusing a product can be environmentally effective in terms of impacts eliminated during manufacturing (e.g. by resource saving) and EoL (e.g. by avoiding disposal). However, it is reasonable to consider the waste hierarchy as a general philosophy, even though the strategy is not necessarily always the most practicable environmental option (Price and Joseph, 2000). Therefore, although there is potential environmental value in pursuing reuse, this must be done based on specific assessments rather than indiscriminately (Price and Joseph, 2000). Even the European Union (EU) Waste Framework Directive (EU, 2008) opens its Article 4(2) by discussing potential deviations from the waste hierarchy for specific waste

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streams “where this is justified by life cycle thinking on the overall impacts of the generation and management of such waste”. From an environmental perspective, the product's design and manufacturing should target the “optimum product life”, rather than maximising it (Cooper, 1994).

With regard to extending a product's lifetime through, for example, repair (Ardente and Mathieux, 2014a; Bobba et al., 2016), there is probably a break-even point at which remanufacture is no longer convenient and it becomes environmentally preferable to discard the product and replace it with a new model that performs better and has more functions. In particular, reusing a product (or some of its components) could reduce the environmental impacts of its manufacture but could also generate greater environmental impacts in other life-cycle phases, for example during use (because of higher energy consumption or the need for more frequent maintenance). Moreover, the quality, and hence the expected lifetime, of reused products is not necessarily as high as that of those manufactured more recently.

From a policy point of view, the importance of reuse and remanufacturing has been demonstrated by its inclusion in the circular economy concept. In a recent meeting of the G7, the forum of the world's seven most industrialised economies, remanufacturing, refurbishment, repair and direct reuse were identified as priority sectors for targeting by the forum's activities (EC, 2017a). At EU level, the introduction of the recent Circular Economy Action Plan cites remanufacturing as a promising strategy (EC, 2015a). So far, however, implementing this action plan has not involved concrete policy measures to target remanufacturing (EC, 2017b), other than funding opportunities through the research framework. Therefore, exploration of how and in which applications remanufacturing could confer the greatest environmental benefits is recommended. It is also worth mentioning that the European Commission issued a standardisation mandate to develop standards covering the material efficiency of products (EC, 2015b). This mandate specifically included a deliverable on defining the methods relevant for assessing the possibility of product reuse and remanufacture (expected by 2019).

At a policy/regulatory level, it is always recommended to clearly identify some (and, as far as possible, to limit the number of) reference definitions. This is particularly true for the guidelines on identifying new and reused products. In terms of EU legislation, such indications are given in the Blue Guide (EC, 2016). This document stipulates that “the Union harmonisation legislation applies to newly manufactured products but also to used and second-hand products, including products resulting from the preparation for re-use of electrical or electronic waste. […] A product, which has been subject to important changes or overhaul aiming to modify its original performance, purpose or type after it has been put into service […] must be considered as a new product. […] Products which have been repaired or exchanged (for example following a defect), without changing the original performance, purpose or type, are not to be considered as new products. […] If the original performance of a product is modified (within the intended use, range of performance and maintenance originally conceived at the design stage) because the spare-parts used for its repair perform better due to technical progress, this product is not to be considered as new. […] Thus, maintenance operations are basically excluded […]” (EC, 2016). The economic benefits of reuse have been shown for very different types of product, including furniture (Alexander and Smaje, 2008), clothes (Joung and Park-Poaps, 2013), building materials (Ayea et al., 2012) and electrical and electronic equipment (EEE) (Geyer and Doctori Blass, 2010). Authors showed that “reuse offers a much better preservation of value compared to recycling, while also providing reduced economic and environmental impacts” (Netherland Circulair, 2015). Several scientific articles have investigated the potential environmental benefits associated with remanufacturing (Kerra and Ryana, 2001; Lindahl et al., 2006; Boustani et al., 2010; Sundin and Lee, 2012; Wang et al., 2014; Wilson et al., 2014). These articles mostly focus on specific case-study assessments (including economic analysis and environmental assessment following a life-cycle approach). Studies on the automotive sector dominate the literature (Amaya et al., 2010; Warsen et al., 2011; Yang et al., 2015; Latham, 2016), especially on the reuse of components such as fuel injectors in trucks or manual transmission.

Cooper and Gutowski (2015) provided a review of studies on the environmental impacts of reusing products, with a special focus on energy consumption. They concluded that the energy and materials needed to return a product or component at EoL to a usable condition are typically minimal compared with those required for new production. “If the product is powered, the environmental impact of the use phase is often dominant and this implies the relevance that short-lived products are fully restored to their original efficiencies” (Cooper and Gutowski, 2015). However, Cooper and Gutowski (2015) did not refer to methods in the literature that took into account the environmental effects of energy efficiency in reused products. Other interesting research was carried out by Ovchinnikov et al. (2014), who introduced an analytical method for the economic and environmental assessment of the remanufacturing process from a business viewpoint. Ovchinnikov et al. (2014) concluded that, in the majority of cases, remanufacturing decreases both costs and energy consumption. However, they did not formalise a comprehensive and systematic method for assessing the remanufacture of a generic product from an environmental perspective. Sakao and Mizuyama (2014) also highlighted the interest in further research into the scientific and quantitative understanding of remanufacturing design.

Methods for an environmental analysis of the trade-off between older and newer models of energy-related products (ErPs) have been investigated already (Ardente and Mathieux, 2014a; Bobba et al., 2016). These have been developed within the framework of REAPro, the “Resource Efficiency Assessment of Products” method proposed by Ardente and Mathieux (2014b). In particular, REAPro assesses the material efficiency of ErPs from various perspectives (i.e. recyclability, recycled content, content of hazardous substances and valuable resources, durability) using life-cycle-based environmental indicators. However, a systematic and general method taking into account the environmental trade-off of remanufacturing ErPs has not yet been proposed.

Remanufacturing can be a relevant strategy for resource conservation and can improve a product's life-cycle performance. However, the literature and legislation do not have a common understanding of how remanufacturing relates to other types of reuse and, more relevantly, if a remanufactured ErP can effectively produce some environmental benefits.

This article introduces a method for assessing, from a life-cycle perspective, the potential environmental benefits of reusing a product or some of its components, and the break-even point of remanufactured products with lower energy efficiency. This method and the related indicators complement the criteria used for assessing the resource efficiency of products within REAPro.

The article first presents an analysis of types of reuse, including remanufacturing, and suggests possible definitions of the term. It then introduces a method to assess for the environmental benefits of a remanufactured ErP. Subsequently, a case study of enterprise servers[1] shows how the method can be used and how the results

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[1] The article analyses the case study of an “enterprise server”. The following sections will simply refer to it as a “server”.

can be interpreted. The last part of the article discusses the limitations of the method and possible developments.

2. Towards a classification of different types of reuse

An analysis of the literature and legislation shows that terms related to different types of reuse are sometimes confused or used synonymously.

Reuse is the action of utilising again a certain product or some of its components.[2] Several definitions of “reuse” are provided in legislation (e.g. EU, 2002; EU, 2008), standards (ISO, 2002; BSI, 2009) and scientific articles (King et al., 2006; Paterson et al., 2016).

Interestingly, the terms “reuse” and “re-use” are used equally in the literature, although the former seems to be preferred in scientific articles whereas the latter is more common in recent legislation and standards. Without entering into a linguistic analysis, our possible interpretation of this heterogeneous use of terms is that “re-use” focuses more attention on the repetition of the use, while “reuse” can be perceived as relating to a self-standing, new operation. The use of terminology has also been the subject of a specific analysis by Paterson et al. (2016). The term “reuse” is used in the present article.

The terms used can be even more varied when incorporating different types of reuse, such as reuse as a second-hand product (Farrant et al., 2010; Geyer and Doctori Blass, 2010); preparing for reuse (Bovea et al., 2016; Tecchio et al., 2016); remanufacturing (King et al., 2006; Paterson et al., 2016); refurbishing (Ijomah and Danis, 2012); reconditioning (BSI, 2009; Ijomah and Danis, 2012); and repurposing (Rogers et al., 2013; Zink et al., 2014).

In an attempt to summarise and align the terminology, Fig. 1 is an original flow chart for classifying types of reuse using definitions from EU- and national-level policies and standards. Such consolidated classification becomes particularly relevant when taking into account that the different types of reuse are being addressed in various policies as part of the EU's Circular Economy Action Plan (EC, 2015a). As shown, the initial definition can depend on the process input: “preparing for reuse” aims to bring reusable objects that have been discarded as waste in line with legal requirements (EU, 2008). If a product is reused for a purpose other than that for which it was designed, it can be defined as repurposed. Finally, depending on the level of treatment undertaken and the quality of the output, reuse can be further subdivided into remanufacture, reconditioning and reuse as a second-hand product. Refurbishing is considered a synonym of reconditioning[3] (BSI, 2009). The present article focuses on an assessment of remanufacturing that relates to reusing a product with a performance that is the same as (if not better than) that of a new product. It is important to highlight that, although the British Standards Institution (BSI) definition (2009) refers to a process involving the whole product, remanufacturing can also focus on reusing some specific components (generally those that have a higher value). For this reason, the definition of remanufacturing in Fig. 1 has been modified from that of the BSI (2009) to also refer to the reuse of components. Remanufacturing differs from reconditioning (or refurbishing), which instead delivers a product of a lower grade (characterised by, for example, a lower warranty).

The classifications in Fig. 1 omit other generic terms (such as repair, maintenance or overhaul) that do not necessarily refer to reuse activities.

3. Method for the environmental assessment of a remanufactured product

The method for the environmental assessment of a remanufactured product is based on the comparison of two product systems: scenario A, the base-case manufacturing scenario, in which product “A” is initially manufactured as usual (i.e. including all new components); and scenario B, the remanufacturing scenario, in which product “B” is manufactured using some components from a used server. Fig. 2 illustrates the system boundaries and processes included in each scenario.[4] If a whole product is fully reused, no “new components” are used as input in the remanufacturing scenario.

The potential environmental impact of each scenario (I_A and I_B) is calculated for each impact category “j” as:

$$I_{A,j} = P_{A,j} + M_{A,j} + O_{A,j} + E_{A,j} \tag{1}$$

$$I_{B,j} = P_{B,j} + P_{RE,j} + M_{B,j} + O_{B,j} + E_{B,j} \tag{2}$$

The symbols used in Equations 1 and 2 are described in Table 1.

Remanufacturing implies that used components are collected and transported to remanufacturing facilities and, when necessary, these are disassembled, checked, tested, cleaned, repaired and determined to be safe and fully functional for placing back on the market (Sundin, 2004). In the remanufacturing scenario, the process for reusing components can generate some environmental impacts (defined as “P_{RE}”) due to, for example, consuming energy or using materials for transporting, testing, repairing and cleaning.

Subsequently, the difference “**Δ**” in the impacts of the scenarios is calculated as:

$$\begin{aligned}\Delta_j &= I_{A,j} - I_{B,j} \\ &= \left(P_{A,j} - P_{B,j} - P_{RE,j}\right) + \left(M_{A,j} - M_{B,j}\right) + \left(U_{A,j} + REP_{A,j} - U_{B,j} \right. \\ &\quad \left. - REP_{B,j}\right) + \left(E_{A,j} - E_{B,j}\right)\end{aligned} \tag{3}$$

Positive values of “Δ” represent an environmental benefit related to the reuse of components in the remanufactured product, compared with the base-case manufacturing process. Negative values of “Δ” imply that the remanufactured product has a higher overall environmental life-cycle impact. It is, therefore, important to identify if, for a given impact category, it follows that $\Delta \geq 0$.

$$\begin{aligned}&\left(P_{A,j} - P_{B,j} - P_{RE,j}\right) + \left(M_{A,j} - M_{B,j}\right) + \left(REP_{A,j} - REP_{B,j}\right) \\ &\quad + \left(E_{A,j} - E_{B,j}\right) + \left(U_{A,j} - U_{B,j}\right) \geq 0\end{aligned} \tag{4}$$

According to Equation (4), environmental benefits can also occur when the remanufactured product (scenario B) consumes more energy than the base-case product (scenario A), as all environmental impacts throughout the whole product life cycle (and not only during use) have to be taken into account.

As mentioned in the introduction, this paper's proposed

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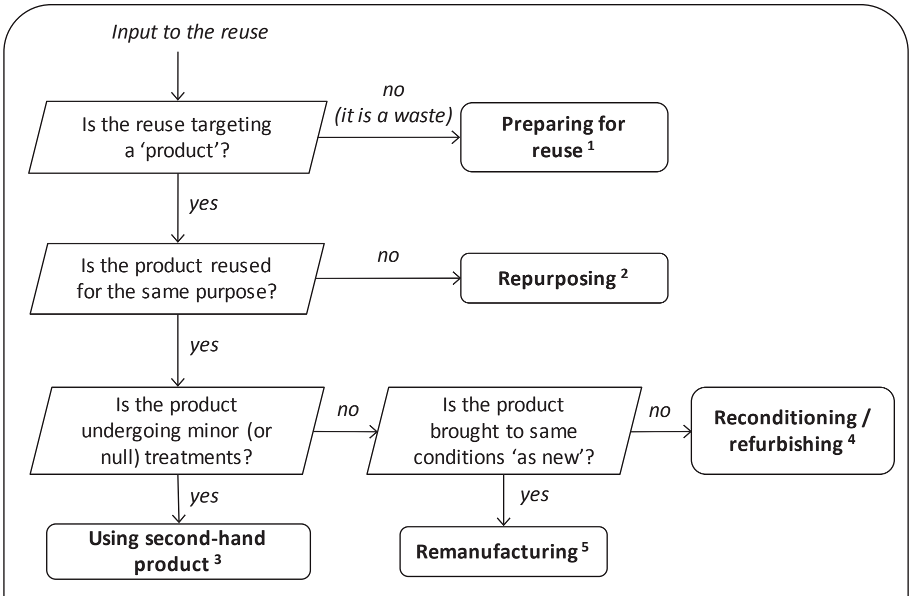
[2] Components can be defined as “parts or small assembly of parts used as part of a larger assembly” (BSI, 2009).

[3] It is highlighted that bare infinite and “-ing” form are sometimes used synonymously by legislation, literature and standards (e.g. both “recondition” and “reconditioning” are used in BSI (2009)). In this article, the “-ing” form has been preferred for the definitions.

[4] The system boundaries of scenario B are set taking into consideration that some components of the waste product are disassembled and utilised for remanufacturing. The impacts due to the initial manufacturing of these reused components are not considered. Similarly, potential benefits due to the elimination of the EoL treatment of these reused components are not taken into account. These assumptions imply that reused components do not have an environmental impact (or benefit) deriving from the product system that generated them.



Definitions:

[1] **Preparing for reuse** "means checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be reused [...]" (EU, 2008).

[2] **Repurposing** means to "utilize a product or its components in a role that it was not originally designed to perform" (as the definition of "repurpose" by BSI (2009)).

[3] **Second-hand product** "shall mean tangible movable property that is suitable for further use as it is or after repair [...]" (as the definition of "second-hand good" by European Council (2006)).

[4] **Reconditioning (or refurbishing)** means to "return a used product to a satisfactory working condition by rebuilding or repairing major components that are close to failure, even where there are no reported or apparent faults in those components" (as the definition of "recondition" by BSI (2009)).

[5] **Remanufacturing** means to "return a used product [or component] to at least its original performance with a warranty that is equivalent or better than that of the newly manufactured product" (modified from the definition of "remanufacture" by BSI (2009), with the addition of the term within brackets).

Fig. 1. Classification and definitions of types of reuse (European Council, 2006).

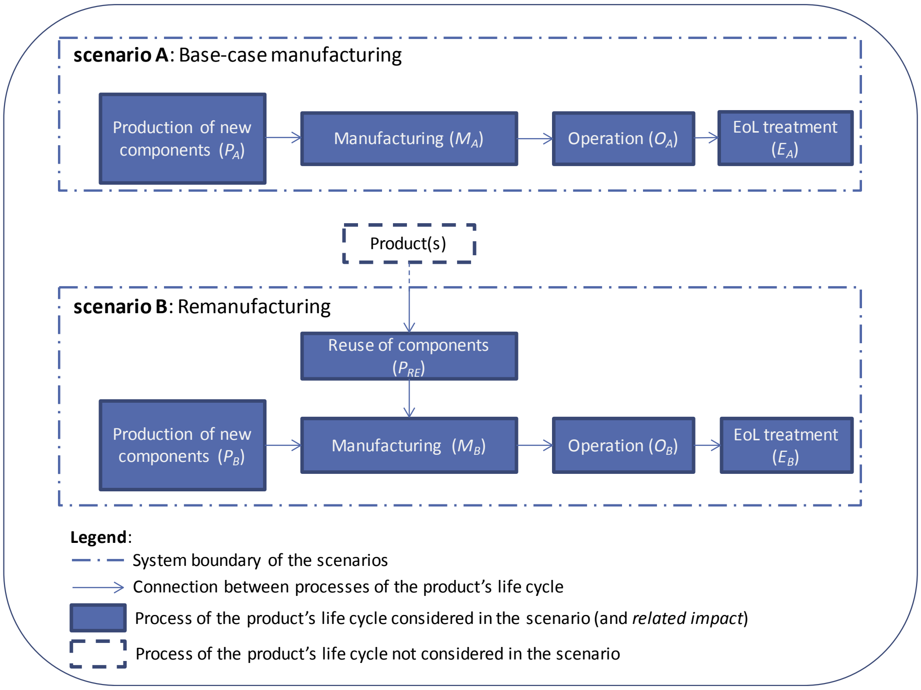


Fig. 2. System boundary of the considered scenarios: scenario A, base-case manufacturing (in which all components of the products are newly manufactured); and scenario B, remanufacturing (in which some components of the products are reused from other products).

Table 1
Symbols and equations for the calculation of impacts in the base-case and remanufacturing scenarios.

$\boldsymbol{I_{A,j}}$	Potential environmental impact of the life cycle of product "A" relative to impact category "j" (per unit of mass).
$\boldsymbol{I_{B,j}}$	Potential environmental impact of the life cycle of product "B" relative to impact category "j" (per unit of mass).
$\boldsymbol{P_{A,j} = \sum_i^{n_A} I_{i,j}}$	• $P_{A,j}$ = potential environmental impact from producing components of product "A" (base-case scenario); • $I_{i,j}$ = potential environmental impact from producing the ith component, relative to the impact category "j" (per unit of mass); • n_A = number of components of product A.
$\boldsymbol{P_{B,j} = \sum_i^{n_B} I_{i,j}}$	• $P_{B,j}$ = potential environmental impact from producing new components of product "B" (remanufacturing scenario); • $I_{i,j}$ = potential environmental impact from producing the ith component, relative to impact category "j" (per unit of mass); • n_B = number of new components in product B.
$\boldsymbol{P_{RE,j}}$	Potential environmental impact, relative to the impact category "j", resulting from the reuse of components for the remanufacturing scenario. Reused components are extracted from other products (during some stages of their life cycles) and are used as inputs for the remanufacturing of product "B".
$\mathbf{M_{A,j}; M_{B,j}}$	Potential environmental impact from manufacturing product "A" and product "B", relative to impact category "j".
$\boldsymbol{O_{A,j} = U_{A,j} + REP_{A,j}}$	• $O_{A,j}$ = potential environmental impact from operating product "A", relative to impact category "j"; • $U_{A,j}$ = potential environmental impact from using product "A", relative to impact category "j"; • $REP_{A,j}$ = potential environmental impact from repair and maintenance during the operation of product "A", relative to impact category "j".
$\boldsymbol{U_{A,j} = e_A \times I_{e,j} \times l_A}$	• e_A = yearly energy consumption of product "A" during use [MJ/year]; • $I_{e,j}$ = potential environmental impact per unit of energy (relative to impact category "j") [impact/MJ]; • l_A = life of product A [years].
$\boldsymbol{O_{B,j} = U_{B,j} + REP_{B,j}}$	• O_B = potential environmental impact from operating product "B", relative to impact category "j"; • U_B = potential environmental impact from using product "B", relative to impact category "j"; • $REP_{B,j}$ = potential environmental impact from repair and maintenance during the operation of product "B", relative to impact category "j".
$\boldsymbol{U_{B,j} = e \times I_{e,j} \times l_B}$	• e_B = yearly energy consumption of product "B" during use [MJ/year]; • $I_{e,j}$ = potential environmental impact per unit of energy (for impact category "j") [impact/MJ]; • l_B = life of product "B" [years].
$\boldsymbol{E_{A,j}; E_{B,j}}$	Potential environmental impact of the end of life of products "A" and "B", relative to impact category "j".

assessment of remanufactured products builds on REAPro, which has already been used to support the EU's environmental product policies for the assessment of various criteria: recyclability, recoverability, recycled content, use and management of relevant materials and hazardous substances, and durability (Ardente and Mathieux, 2014b; Talens Peiró and Ardente, 2015; Bobba et al., 2016). The new method proposed here could be especially useful for analysing the trade-off between a product manufactured using new components and a product that has reused components, even if this results in a remanufactured product having a lower energy class. Assessing remanufactured products differs in several ways from assessing the extension of a product's operation (Bobba et al., 2016), as follows:

- The system boundaries are set based on the assumption that a remanufactured product is functionally equivalent to (substitutes) a new product (also in terms of average life). The analysis by Bobba et al. (2016) assumes that the life of a product could be extended (e.g. through repair) for a limited time, delaying the purchase of a new product by several years.

The focus of the method proposed is on the production process led by the original equipment manufacturer (OEM). It tackles the question of whether or not the reuse of certain components in the OEM's production system is environmentally beneficial from a life-cycle perspective. The method used by Bobba et al. (2016) focused on the convenience of using a certain product for longer, instead than replacing this with a new one (and potentially more efficient in terms of energy consumption).

- The specific parameter "P_{RE}" is introduced to model the potential environmental impacts of remanufacturing the product. Overall, the number of parameters in the assessment of remanufacturing is smaller than that in the method used by Bobba et al. (2016), with, consequently, a lower amount of information needed and easier calculations.

To simplify the assessment for scenario B (reusing the components) (i.e. when $\Delta \geq 0$), the following additional assumptions could be introduced:

- Products A and B have the same composition. Therefore, the difference ($\Delta P_j = P_{A,j} - P_{B,j}$) amounts to the potential environmental impacts of the components that are new in scenario A and reused in scenario B. This difference can be expressed as $\Delta P_j = P_{A,j} - P_{B,j} = \sum_i^{n_{reused}} I_{i,j}$

  Where the symbols not previously used are:

  - n_{reused} = number of components reused during remanufacturing (scenario B);
  - $I_{i,j}$ = potential environmental impact (relative to the category "j") of the ith component.

This assumption can be considered frequently occurring, since remanufactured products provide the same main function as the OEM's new products, which can include some different specifications between models. Moreover, manufacturers tend to avoid differentiating mass production lines to minimise possible technical complications.

- Based on the previous assumption on the composition, the manufacturing processes for scenarios A and B are assumed to be equal (i.e. $M_{A_j} = M_{B_j}$).[5]
- The environmental impacts of the EoL treatments in both scenarios are assumed to be equal (i.e. $E_{A,j} = E_{B,j}$). The EoL treatments for products A and B generally do not change unless a special situation occurs, for instance if their hazardous substances content is different and dedicated depollution treatments are needed.

Based on the previous assumptions, Equation (4) becomes:

$$(\Delta P_j - P_{RE,j}) + (REP_{A,j} - REP_{B,j}) + (U_{A,j} - U_{B,j}) \geq 0 \qquad (5)$$

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[5] This assumption implies that the manufacturing process is independent of the origin of the components (i.e. new or reused).

The potential environmental impact of using product B can be expressed as a function[6] of product A as $\left(\delta_j = \frac{U_{B,j}}{U_{A,j}}\right)$ being $(\delta_j \geq 0)$. This can also be written as $(U_{B,j} = \delta_j \Delta U_{A,j})$, and can be integrated into the previous equation as:

$$(\Delta P_j - P_{RE,j}) + (REP_{A,j} - REP_{B,j}) + U_{A,j}(1 - \delta_j) \geq 0 \qquad (6)$$

or alternatively as:

$$\delta_j \leq 1 + \frac{(\Delta P_j \ - PRE_j) \ + \ (REP_{A,j} - REP_{B,j})}{U_{A,j}} \qquad (7)$$

In conclusion, remanufacturing is environmentally convenient when the condition set in Equation (7) is satisfied. Assuming that the maintenance of the two products is equal[7] (i.e. $REP_A \approx REP_B$), Equation (7) becomes:

$$\delta_j \leq 1 + \frac{(\Delta P_j - PRE_j)}{U_{A,j}} \qquad (8)$$

Given that “δ” has been ARAG.

Zdefined as $\left(\delta_j = \frac{U_{B,j}}{U_{A,j}}\right)$, the situation $(\delta_j > 1)$ means that the remanufactured product (i.e. product B) has more of an environmental impact during the operation (e.g. because of higher energy consumption). Based on Equation (8), we can consider that this remanufactured product is still environmentally convenient if $(\Delta P_j > PRE_j)$, or, in other words, if the environmental impacts due to the manufacturing of new components (as in scenario A) are greater than the impacts due to remanufacturing (scenario B). Equation (9) shows the particular case in which the environmental impacts of scenarios A and B are equivalent:

$$\delta_j = 1 + \frac{(\Delta P_j - PRE_j)}{U_{A,j}} = 1 + \frac{\left(\sum_i^{n_{reused}} I_{i,j} - PRE_j\right)}{U_{A,j}} \qquad (9)$$

Bearing in mind that Equation (8) is, in mathematical terms, an inequality, its conceptual meaning is the following: considering the *jth* environmental impact, the higher the value (in absolute terms) of the right-hand term of Equation (8), the wider the allowed difference between $U_{A,j}$ and $U_{B,j}$, i.e. between the potential environmental impact from using a new product (scenario A) and that from using a remanufactured product (scenario B). In such cases, although $U_{B,j}$ would be significantly higher than $U_{A,j}$, the remanufactured product would be still more environmentally effective from the point of view of the *jth* environmental impact. Environmental impacts for which the right-hand term of Equation (8) has a higher value (in absolute terms) are typically those for which the effect of use is much less significant than the effect of other life-cycle phases (such as the “human toxicity” impacts that largely depend on the impacts of production).

4. Applying the method to the case study of remanufacturing a server

A practical application of the method described in section 3 is discussed here. This section presents the results of a case study carried out in parallel with the technical preparatory work for developing potential requirements for the circular economy of enterprise servers, in the framework of implementing the Ecodesign Directive (EU, 2009) at EU level (see Box 1). Enterprise servers are computers used for business-to-business applications, typically in data centres or server rooms. There are three reasons for choosing this product group. First, market projections suggest that the environmental impact of these products is judged to be significant already and expected to increase in the medium term, given the trends in the information and communications technology (ICT) sector, such as the ‘internet of things’ and ‘cloud computing’, which are growing very quickly and require more and more computing power. Second, servers could have significant environmental savings potential from a material efficiency point of view, making them an interesting product to analyse. Third, the aforementioned research and policy work is ongoing; therefore, the findings and preliminary conclusions described here show how the decision-making process, at a policy level, benefits from the supporting technical and scientific work. Moreover, Cole et al. (2017) recently observed that “reuse works best for relatively expensive or infrequently used products that retain value beyond their first use”, which is particularly relevant to servers.

Box 1

The EU Ecodesign Directive

The EU Ecodesign Directive (EU, 2009) allows minimum requirements to be set for products in the EU market to improve their environmental performance, e.g. by setting minimum energy efficiency levels (as is frequently the case) or by declaring the content of certain hazardous substances. The “Ecodesign” Directive is complemented by the Energy Labelling Directive (EU, 2010), with its well-established green-to-red “A” to “G” scale. This legislative framework is judged to be one of the most effective policy instruments at EU level for promoting energy efficiency. Ecodesign, complemented by energy labelling, helps to strengthen the EU's competitiveness, to boost job creation and economic growth, and to save consumers money while reducing CO_2 emissions. In the context of the Circular Economy Action Plan (EC, 2015a), the “Ecodesign” Directive has a relevant role, with the aim of developing requirements, on a case-by-case basis, for making products easier to repair, dismantle and recycle. The preparatory work for any “Ecodesign” policy measure is a complex yet interesting exercise that entails technical, procedural and legal steps. Specific product groups, once they are listed in an “Ecodesign working plan”, are first analysed in a preparatory study, where the feasibility of proposing “Ecodesign” (and/or energy labelling) measures is investigated in detail. The next step is an impact assessment, through which various policy options are analysed, in particular from the perspective of cost competitiveness and the impacts on small and medium-sized enterprises, on technological development and innovation, on product functionality and on end-user affordability. Further procedural and legal steps take

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[6] This expression refers to the remanufactured product's energy consumption as a percentage of the base-case product's consumption. This assumption is particularly effective, since the energy consumption of the base-case product is generally a known value, and the ratio δ is a parameter that can be assumed within certain ranges of variability.

[7] In this assumption, this is also is very likely, since maintaining a product is generally not dependent on whether the components are remanufactured or new.

place, in case the analysis performed in the impact assessment confirms that a potential ecodesign (and/or energy labelling) measure is feasible and effective to the extent that it sustainably decreases the environmental impact of a certain product group.

After including servers in the Ecodesign Working Plan 2012–2014 (EC, 2012), the European Commission has been analysing this area for potential legislation. The preparatory study (Berwald et al., 2014) ended in September 2015 and indicated that an "Ecodesign Regulation" was the most suitable policy option for this product group. In parallel with the "Ecodesign preparatory study", the Joint Research Centre (JRC), the in-house science and knowledge service of the European Commission, developed a study on servers (Talens Peiró and Ardente, 2015). The objectives of this study focused on material efficiency aspects and identifying ways to improve the reuse and recycling of servers. A key point for detailed study was the reuse of components because servers have a high number of electronic components, and thus there is a possible trade-off between keeping and repairing them and replacing them with new ones, given the rapid development of information technology. The study provided support for the policy process (Polverini and Tosoratti, 2016) as well as first-hand information and data from OEMs, reuse companies and independent operators. Table 2 provides the technical description (including manufacturing year, details of some parts, power consumption, use pattern, lifetime and overall mass) of the rack-optimised server used in the JRC study, and is thus used in this paper to illustrate the method for assessing remanufacturing.

As a result of the synergetic work on servers performed as part of the "Ecodesign preparatory study" (Berwald et al., 2014) and the JRC study on material efficiency aspects of servers (Talens Peiró and Ardente, 2015), several potential ecodesign requirements have been proposed. For example, in relation to energy efficiency, a quantitative requirement on the efficiency of the internal power supply unit was suggested. The potential non-energy-related requirements for servers were the extraction of key components and those containing critical raw materials, the availability of built-in software for data deletion and the availability of the latest firmware for updates and maintenance.

4.1. Assumptions and potential environmental impacts for the base case (scenario A)

When analysing a server for reuse, the first step is calculating the life-cycle impacts of the base-case server. The functional unit of the study was the use of one average server (27.8 kg in mass) for 4 years of its lifetime. The analysis refers to the base-case server defined in the "Ecodesign preparatory study", considered as the average server in the European market (Berwald et al., 2014). Table 3 lists the bill of materials (BoM) of the case-study server. The details of the composition of some components were derived from data of the "Ecodesign preparatory study" (Berwald et al., 2014) and from two exemplar servers dismantled by the JRC during the study.

The system boundaries of the analysis include manufacturing raw materials and components, listed in Table 3; assembling the server; transport; the use phase; and the EoL. Table 4 summarises the main assumptions when calculating life-cycle impacts. Impact categories are selected in accordance with the recommendations of the International Reference Life Cycle Data System (ILCD) (EC, 2010) handbook,[8] available in the GaBi software (PE, 2017). Table 5 summarises the potential environmental impacts of a server's life cycle.

Table 2
Technical description of the server under study (BIO Intelligence Service and Fraunhofer IZM, 2015).

	Technical description
Manufacturing year	2012
Number of central processing units (CPUs)	2 CPU socket (Intel E5-26XX), typical configuration according to Server Efficiency Rating Tool (SERT) (average 2.3 GHz)
Number of fans	4 (4–5 W at 25–50% load and 12–15 Watt per fan at maximum load or higher temperatures (30 °C))
Number of hard disk drives (HDDs)	4
Number of power supply units (PSUs)	2 × 400 W (AC/DC)
Power consumption according to SERT	idle: 150 W/25% Load 200 W
Power consumption/year	1661 kWh
Use	5 h at idle + 19 h at 25%load * 365 days
Infrastructure Overhead	Power usage effectiveness (PUE): 2.0

4.2. Assumptions and potential environmental impacts of remanufacturing (scenario B)

Both OEMs and so-called third-party operators can remanufacture servers. OEMs usually have a service called "asset recovery" to manage servers under lease. One of the objectives of this service is to collect servers at the end of their use and refurbish them to suit new customers with less demanding technical requirements. Some parts of the collected servers remain in stock and others are sent to be recycled. In the remanufacturing scenario (scenario B), OEMs collect servers at the end of their use and then identify and cross-check the servers' parts. Parts that are in high demand and still function are taken and stocked as potentially reusable. The remaining parts are sent to a specialised recycling facility, similar to scenario A.

Table 6 details the components most frequently reused in servers in scenario A. The indicative reuse rate of such components (i.e. the proportion of components that are effectively reused) has been calculated based on data from an ICT company specialised in repairing, reusing and providing spare parts (Re-Tek, 2015). For example, hard disk drives (HDDs) contained in servers are reused in 47.7% of cases. The reliability of these figures has been confirmed, by personal communication, by Free ICT Europe, a non-profit foundation representing independent ICT repair and refurbishing companies in Europe (Van Oostrum et al., 2017). The figures were presented to stakeholders during an "Ecodesign preparatory study" meeting. One of the observations was that power supply units are reused in repaired/refurbished products but generally not reused in remanufactured products. Table 7 shows the potential environmental impacts of the manufacturing of components more commonly reused.

Based on the reuse rates given in Table 6, scenario B could be further split into two possible scenarios: scenario B.1, which assumes that only HDDs and memory cards are reused; and scenario B.2, which, more optimistically, assumes that the central processing units (CPUs) and mainboard are also reused. The analysis of these two remanufacturing scenarios (B.1 and B.2) and the comparison with scenario A are discussed in the following section.

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[8] Compared with the ILCD recommendations, the "land use" impact category has been excluded because of the high uncertainty related to the life-cycle inventory data available in LCA databases. The impact category "resource depletion" has been split into "abiotic depletion potential (ADP)" (CML, 2015) and "primary energy demand from renewable and non-renewable resources (gross cal. value) [MJ]".

Table 3
Bill of materials of the case-study server.

Component	Details/materials	Mass (g)	Component	Details/materials	Mass (g)
Chassis	Steel	12 265	Main board	Controller board (various material)	1667
	Plastics (ABS)	348			
	Plastics (PC)	282	2 power supply units	Various materials	3426
	Aluminium	249	Expansion card/other	Printed circuit board (PCB) (various materials)	349
	Copper	179	Cables	Brass	7
	PCB	131		Copper	81
4 fans	Various	946		Zinc	96
4 HDDs	Various	1748		Plastics (HDPE)	104
Optical disk drive	Low-alloy steel	115		Plastics (PVC)	145
	Copper	7		PUR	2
	Aluminium	1		Synthetic rubber	35
	Plastics (HDPE)	28	2 central power units (CPU)	Various materials	54
	Plastics (ABS)	12	Heat pipes for CPUs	Low-alloy steel	140
	Plastics (PC)	7		Copper	442
	Printed circuit board (PCB) (various materials)	19	Memory	Printed circuit board (PCB) (various materials)	135
			Packaging	Cardboard	3629
Batteries	CR2032 (button)	1.6		Plastics (HDPE and other)	78
	Lithium ion (prismatic)	43		Plastics (GPPS/Styrofoam)	1026
TOTAL: 27.8 kg					

ABS: acrylonitrile butadiene styrene; HDPE: high-density polyethylene; PC: polycarbonate; PUR: polyurethane; PVC: polyvinyl chloride.

Table 4
Assumptions when calculating the environmental impacts of a server's life cycle in the base case (scenario A).

Life-cycle stage	Assumptions
Manufacturing	The environmental impacts of raw materials and the components used in the server were derived from the GaBi and Ecoinvent databases (PE, 2017) and Hischier et al. (2007)
Assembly	Energy used in assembling the components in a server and checking its operability is estimated to be 6.5 kWh (OVH, 2014)
Transport	Overall transport distance of 20 500 km (19 000 km by a container ship; 1400 km by 22-tonne lorry)
Use phase	- Lifetime is 4 years at 365 days of active utilisation per year - The annual power consumption is 1661 kWh - Use pattern: 5 h in idle mode (the server is not asleep, but no applications are running); 19 h at 25% load (executing tasks with a CPU load of 25%)
End of life	- Wasted servers are collected by specialised recyclers, and transported 200 km by lorry to the recycling facility - Servers are manually pre-processed to extract some parts as required by waste legislation. The environmental impact of the manual disassembly is considered negligible - Then, using the recycling technologies on site, servers are shredded and various materials are sorted and recovered. Plastics obtained after shredding are incinerated (with energy recovery), while the recovered metals are used for secondary raw material production. The electricity for shredding and sorting is estimated to be 65.6 kWh per tonne of waste (Huisman, 2003)

Table 5
Summary of the environmental impacts of the life cycle of the case-study server in the base case (scenario A).

Environmental impact categories	Potential environmental impact of the server			
	Manufacturing	Use	EoL	Units
Abiotic depletion potential (elements)	0.11	0.001	−0.07	[kg Sb-eq.]
Acidification midpoint	6.12	9.60	−2.4	[Mole H+ eq.]
Climate change midpoint (excluding biogenic carbon)	858.3	3077.2	−58.9	[kg CO2-eq.]
Ecotoxicity: freshwater	1141.8	86.4	−745.7	[CTUe]
Eutrophication: freshwater	0.03	0.01	−0.02	[kg P eq]
Eutrophication: marine	0.04	0.19	−4.8E-03	[kg N-eq.]
Eutrophication: terrestrial	9.71	18.93	−1.5	[Mole N eq.]
Human toxicity, cancer effects	1.72E-05	2.54E-06	−3.0E-06	[CTUh]
Human toxicity, non-cancer effects	8.30E-05	6.48E-05	−2.3E-05	[CTUh]
Ionising radiation, human health	42.2	1300.3	−8.3	[kBq U235 eq]
Ozone depletion	7.00E-06	2.18E-06	−3.5E-06	[kg CFC-11 eq]
Particulate matter/respiratory inorganics	0.7	0.5	−0.13	[kg PM2.5-eq.]
Photochemical ozone formation, human health	2.7	5.0	−0.47	[kg NMVOC]
Primary energy demand (from fossil and renewable sources)	12 724.0	71 500.5	−696.4	[MJ]
Resource depletion (water)	10.0	33.8	−27.12	[m^3 eq.]

5. Results and discussion

5.1. Results

The environmental assessments of the two remanufacturing scenarios (scenarios B.1 and B.2) are calculated using Equation (9) (section 3.1). The results are presented in Table 8. The values of "ΔP_j" indicate the potential environmental impacts of manufacturing reusable components (as in Table 6). To calculate the environmental impacts of the processes for remanufacturing (P_{RE}), the environmental impacts of transporting the used product to the reuse facility are assumed to be similar to those of transporting

Table 6
Reused parts of server and reuse rates (adapted from Re-Tek, 2015).

Component	Mass (g)	Reuse rate (%)	Component	Mass (g)	Reuse rate (%)
HDDs	1750	47.7	Mainboard	1662	2.7
Memory cards	135	40.1	Raid card	5.2	2.1
Processors (CPUs)	54	5.2	Chassis (frames)	13 454	1.4
Power supply	3426	5.0	Expansion card/graphic card	349	0.7

Table 7
Potential environmental impact of manufacturing components more frequently reused in servers.

Environmental impact category	Potential environmental impact of parts more frequently reused from servers								
	HDD	Memory cards	Processor (CPU)	Power supply	Main board	Raid card	Chassis (frame)	Expansion card/ graphic card	Units
Abiotic depletion potential (elements)	1.1E-02	1.3E-02	2.8E-02	4.3E-03	2.9E-02	2.3E-05	4.7E-03	7.8E-03	[kg Sb-eq.]
Acidification midpoint	6.3E-01	9.8E-01	1.5E+00	1.8E-01	1.5E+00	2.2E-03	4.6E-01	3.6E-01	[Mole H+ eq.]
GWP	8.3E+01	1.4E+02	2.0E+02	3.4E+01	2.1E+02	3.7E-01	9.9E+01	5.0E+01	[kg CO_2-eq.]
Ecotoxicity: freshwater	4.2E+01	3.8E+01	5.2E+01	3.3E+01	8.2E+02	1.1E-01	7.5E+01	1.3E+01	[CTUe]
Eutrophication: freshwater	1.2E-03	3.0E-04	1.5E-04	4.5E-04	2.0E-02	5.0E-06	1.2E-03	2.0E-04	[kg P eq]
Eutrophication: marine	3.8E-03	6.9E-03	7.1E-03	2.2E-03	1.5E-02	3.1E-05	2.0E-03	3.1E-03	[kg N-eq.]
Eutrophication: terrestrial	1.0E+00	1.6E+00	2.0E+00	3.2E-01	2.3E+00	4.6E-03	8.2E-01	5.5E-01	[Mole N eq.]
Human toxicity, cancer effects.	1.3E-06	2.6E-06	3.9E-06	6.4E-07	4.2E-06	4.1E-09	2.9E-06	7.7E-07	[CTUh]
Human toxicity, non-cancer effects	6.8E-06	1.1E-05	1.5E-05	4.2E-06	3.2E-05	2.9E-08	6.3E-06	4.2E-06	[CTUh]
Ionising radiation	5.2E+00	6.7E+00	1.1E+01	1.2E+00	9.3E+00	8.7E-03	2.0E+00	2.4E+00	[kBq U235 eq]
Ozone depletion	6.4E-07	3.6E-08	4.9E-08	5.9E-07	1.6E-07	3.1E-11	4.9E-06	1.1E-08	[kg CFC-11 eq]
Particulate matter	6.3E-02	1.0E-01	1.5E-01	3.4E-02	2.2E-01	4.0E-04	3.8E-02	4.6E-02	[kg PM2,5-eq.]
Photochemical ozone formation	2.8E-01	4.3E-01	5.9E-01	9.2E-02	6.4E-01	1.2E-03	2.6E-01	1.5E-01	[kg NMVOC]
Primary energy (fossil + renewable)	1.3E+03	2.3E+03	3.3E+03	4.2E+02	3.2E+03	5.4E+00	5.7E+02	7.7E+02	[MJ]
Resource depletion (water)	1.2E+00	6.3E-01	1.1E+00	2.1E-01	2.5E+00	1.9E-03	2.1E-01	2.6E-01	[m^3 eq.]

Table 8
Environmental assessment of remanufacturing scenarios.

		Remanufacturing scenario							
		B.1 reused: HDDs and memory cards				B.2 reused: HDDs, memory cards, CPU, mainboard			
		ΔP	*PRE*	U	δ	ΔP	*PRE*	U	δ
Abiotic depletion potential (elements)	[kg Sb-eq.]	2.4E-02	1.2E-04	1.0E-03	**24.51**	8.0E-02	4.0E-04	1.0E-03	**80.74**
Acidification midpoint	[Mole H+ eq.]	1.6E+00	8.1E-03	9.6E+00	1.17	4.7E+00	2.3E-02	9.6E+00	**1.48**
GWP	[kg CO_2-eq.]	2.2E+02	1.1E+00	3.1E+03	1.07	6.3E+02	3.2E+00	3.1E+03	1.20
Ecotoxicity: freshwater	[CTUe]	8.0E+01	4.0E-01	8.6E+01	**1.92**	9.5E+02	4.8E+00	8.6E+01	**12.0**
Eutrophication: freshwater	[kg P eq]	1.5E-03	7.4E-06	6.4E-03	1.23	2.2E-02	1.1E-04	6.4E-03	**4.40**
Eutrophication: marine	[kg N-eq.]	1.1E-02	5.3E-05	1.9E-01	1.05	3.2E-02	1.6E-04	1.9E-01	1.17
Eutrophication: terrestrial	[Mole N eq.]	2.6E+00	1.3E-02	1.9E+01	1.14	6.9E+00	3.5E-02	1.9E+01	**1.37**
Human toxicity: cancer effects	[CTUh]	3.9E-06	1.9E-08	2.5E-06	**2.52**	1.2E-05	6.0E-08	2.5E-06	**5.69**
Human toxicity: non-cancer effects	[CTUh]	1.7E-05	8.7E-08	6.5E-05	1.27	6.4E-05	3.2E-07	6.5E-05	**1.98**
Ionising radiation	[kBq U235 eq]	1.2E+01	6.0E-02	1.3E+03	1.01	3.3E+01	1.6E-01	1.3E+03	1.02
Ozone depletion	[kg CFC-11 eq]	6.7E-07	3.4E-09	2.2E-06	**1.31**	8.8E-07	4.4E-09	2.2E-06	**1.40**
Particulate matter	[kg PM2,5-eq.]	1.6E-01	8.2E-04	5.2E-01	**1.32**	5.4E-01	2.7E-03	5.2E-01	**2.03**
Photochemical ozone formation	[kg NMVOC]	7.2E-01	3.6E-03	5.0E+00	1.14	1.9E+00	9.7E-03	5.0E+00	**1.38**
Primary energy (fossil + renewable)	[MJ]	3.6E+03	1.8E+01	7.2E+04	1.05	1.0E+04	5.0E+01	7.2E+04	1.14
Resource depletion (water)	[m^3 eq.]	1.8E+00	9.0E-03	3.4E+01	1.05	5.4E+00	2.7E-02	3.4E+01	1.16

* Values > 1.3 are highlighted in **bold**. These relate to the impact categories for which the benefits of remanufacturing are outstanding.

components during manufacturing. Moreover, it is assumed that the environmental impacts from manually disassembling reused components are negligible. Similarly, the environmental impacts from cosmetic repairs are negligible, since the reused components are all internal and do not need such treatment. Low environmental impacts occur from energy consumption during checking and testing components, and from some potential minor repairs or substitutions (when necessary). According to the manufacturers and remanufacturing companies interviewed, reusable components are discarded when major repairs are required or when there is a high stock of such components. In the absence of more precise figures, the environmental impacts of the processes for remanufacturing "P_{RE}" are assumed to be 0.5% of those for the production of the component (this assumption is further discussed in the sensitivity analysis in section 5.2).

Since the material composition of new and reused components does not differ significantly, it is also assumed that EoL treatments of the remanufactured product will be not affected.

The environmental impact category "global warming potential" (GWP) for product B (scenario B.1) compared with product A (scenario A) is $\delta_{GWP} = 1.07$. Given the definition of $\left(\delta_j = \frac{U_{B\bullet 1,j}}{U_{A,j}}\right)$, the result $\delta_{GWP} = 1.07$ implies that a server remanufactured following scenario B.1 is environmentally beneficial even though it consumes 7% more energy than a server analysed under scenario A. Scenario

B.1 is not environmentally beneficial when the energy consumption of the remanufactured server is more than 7% higher than the energy consumption of a new server. For scenario B.1, similar considerations apply to other environmental impact categories included in the analysis: marine eutrophication, primary energy demand and freshwater consumption. These are, in fact, the impact categories most influenced by electricity consumption during the use phase.

On the other hand, in scenario B.1, values of δ_j are much higher for the other environmental impact categories. This implies that environmental benefits are much more evident for categories more sensitive to environmental impacts during manufacturing. This is particularly the case for “abiotic depletion potential”, which is almost independent of electricity consumption during operation, and thus reusing components always results in environmental benefits. In Table 8, values of δ_j higher than 1.3 have been highlighted in bold, since these can be considered the impact categories for which the benefits of remanufacturing are outstanding.

Comparing the remanufacturing scenarios, values of δ_j in scenario B.1 are greater than those in scenario B.2. Based on this, we can conclude that increasing the number of reused components leads to greater environmental benefits. In particular, in scenario B.2, a δ_{GWP} value of 20% suggests that, even if the remanufactured server consumed 20% more energy than the base-case product, reusing components would still be preferable for the GWP impact category.

5.2. *Limits and uncertainties of the method and sensitivity analysis*

The environmental assessment of products is generally affected by uncertainties typical of life cycle assessments (LCAs), such as system boundary definitions, the quality and representativeness of the inventory data, the availability of primary data versus secondary data, and the selection of the impact categories. The better the quality of the data used as input for the equations in section 3, the more robust the overall assessment. However, since the objective of the present article is to discuss the method proposed for the assessment of remanufacturing, uncertainties arising from lifecycle data (as impacts for material production or energy consumption during the use phase) are not investigated further. The uncertainty analysis that follows focuses on the functionality of the components reused in the servers, and the environmental impacts of remanufacturing.

Although, by definition, a remanufactured product is returned “as new” (i.e. in the same condition as the original product put on the market) (BSI, 2009; EC, 2016), it is possible that, instead of a reused component, an OEM would use an updated version of that component with potentially better performance. This is especially likely to happen for electronic goods whose technology evolves quickly (e.g. HDDs, memory cards and CPUs). Although both of the products (i.e. the products from the two scenarios in Fig. 2) can be considered “as new”, they could have some differences in performance.

In Equation (9), the environmental benefits of reusing components, grouped in the term $\sum_i^{n_{reused}} I_{i,j}$, are calculated, taking into account the fact that manufacturing new components is no longer needed. This means, for example, that by reusing a CPU in a remanufactured server, a new CPU is not required, thus eliminating any environmental impact of its manufacture. It might be that the potential environmental impacts of a newer CPU with better performance (e.g. able to process a greater number of instructions per second) and that of a reused CPU do not differ significantly. In such a case, because a reused CPU is not considered equivalent to a new one, the environmental benefits of reusing the CPU should be discounted. This is in line with the conclusions of Cooper and Gutowski (2015), who stated that it is relevant to assess both the extent to which consumers use a reused product and the product that the remanufactured product is actually replacing. To account more precisely for this, a new parameter, “reuse downcycling factor” (k_i), can be introduced in Equation (10):

$$\delta_j = 1 + \frac{\left(\sum_i^{n_{reused}} k_i \bullet I_{i,j} - PRE_j\right)}{U_{A,j}} \tag{10}$$

The parameter k_i can be estimated for each reused component, “i”, taking into account the effective performance of reused components compared with that of new ones. Reuse downcycling factors are then introduced into the case-study assessment. However, because of a lack of specific data, these factors have been estimated as follows:

- Memory cards and HDDs are the most frequently reused components in remanufactured servers, mainly because they have proved highly reliable and less commonly become technologically obsolete compared to other parts of the server. For these components, it is assumed a factor: $k_1 \in [0.8; 0.9]$.
- Other parts (mainly processors and main boards) are at a higher risk of becoming technologically obsolete and so are used mainly as spare parts for maintenance or installed in refurbished servers with lower levels of performance. For these components, it is assumed a factor: $k_2 \in [0.4; 0.7]$.

For example, a downcycling factor of $k_1 = 0.8$ for an HDD means that the environmental benefits of reusing that HDD are 80% of the potential environmental impact of manufacturing a new one.

The environmental assessment of the remanufacturing scenario for the server was modified using the aforementioned downcycling factors (the results are presented in Table 9). When k_i is equal to 1, the results are the same as those in Table 8. Obviously, the new values of δ calculated in Table 9 are lower than those presented in section 4, as a result of the decrease in the benefits of the reused components. However, small variations of δ are observed for almost all of the impact categories (with the exception of abiotic depletion potential) in scenario B.1. This proves that the assumptions for the downcycling factors have low relevance in this scenario. Larger variations are observed in scenario B.2. For example, δ_{GPW} in scenario B.2 with variable downcycling factors assumes values in the range $[1.07; 1.15]$, lower than the value of $\delta_{GPW} = 1.2$ estimated when downcycling is not accounted for. Furthermore, the largest variations are estimated for abiotic depletion category, although the results of δ are always very high and imply that reuse is environmentally beneficial regardless of whether a product's efficiency is reduced after remanufacturing.

An important limitation of the assessment are the environmental impacts that can be estimated from remanufacturing (represented by the term P_{RE}). Indeed, the treatments for remanufacturing can change depending on the general status of the component in question. The same type of component could require a minor intervention in some situations and more demanding processes in others (e.g. repairing or substituting certain parts). Because of current uncertainties, it is preferable to assume a certain range of variation of the term P_{RE}. In the analysis of remanufactured scenarios (section 5.1), it was assumed that the potential environmental impact $P_{RE,i}$ amounted to 0.5% of the total environmental impact of the production of component “i”. In the following paragraphs, a sensitivity analysis of the results is carried out by assuming that P_{RE} varies from 0.2% to 10%. Values higher than 10%

Table 9
Environmental assessment of remanufacturing scenarios (B.1 and B.2) taking into account downcycling factors (k_i).

		Remanufacturing scenario							
		B.1 reused: HDDs and memory cards			B.2 reused: HDDs, memory cards, CPU, mainboard				
		$k_1 = 1$	$k_1 = 0.8$	$k_1 = 0.9$	$k_1 = 1$ $k_2 = 1$	$k_1 = 0.8$ $k_2 = 0.4$	$k_1 = 0.8$ $k_2 = 0.7$	$k_1 = 0.9$ $k_2 = 0.4$	$k_1 = 0.9$ $k_2 = 0.7$
Abiotic depletion potential (elements)	[kg Sb-eq.]	24.51	19.78	22.15	80.74	42.11	59.06	28.58	35.04
Acidification midpoint	[Mole H+ eq.]	1.17	1.13	1.15	1.48	1.26	1.35	1.17	1.21
GWP	[kg CO_2-eq.]	1.07	1.06	1.06	1.20	1.11	1.15	1.07	1.08
Ecotoxicity: freshwater	[CTUe]	1.92	1.74	1.83	12.00	5.74	8.77	2.20	2.49
Eutrophication: freshwater	[kg P eq]	1.23	1.18	1.21	4.40	2.44	3.40	1.46	1.57
Eutrophication: marine	[kg N-eq.]	1.05	1.04	1.05	1.17	1.09	1.12	1.05	1.06
Eutrophication: terrestrial	[Mole N eq.]	1.14	1.11	1.12	1.37	1.20	1.27	1.14	1.17
Human toxicity, cancer effects	[CTUh]	2.52	2.22	2.37	5.69	3.47	4.43	2.32	2.63
Human toxicity, non-cancer effects	[CTUh]	1.27	1.21	1.24	1.98	1.50	1.71	1.27	1.33
Ionising radiation	[kBq U235 eq]	1.01	1.01	1.01	1.02	1.01	1.02	1.01	1.01
Ozone depletion	[kg CFC-11 eq]	1.31	1.24	1.28	1.40	1.28	1.31	1.76	1.93
Particulate matter	[kg PM2,5-eq.]	1.3	1.3	1.3	2.0	1.5	1.8	1.3	1.4
Photochemical ozone	[kg NMVOC]	1.14	1.11	1.13	1.38	1.21	1.28	1.14	1.18
Primary energy (fossil + renewable)	[MJ]	1.05	1.04	1.04	1.14	1.08	1.10	1.04	1.06
Resource depletion (water)	[m^3 eq.]	1.05	1.04	1.05	1.16	1.08	1.12	1.09	1.11

are excluded, since, according to one OEM interviewed, components that require major repair are generally not able to be reused. Table 10 shows the environmental assessment of remanufacturing scenarios B.1 and B.2 using the new values of $P_{RE,i}$. Variations of δ resulted in very low or negligible results, especially for those impact categories largely influenced by impacts during operation (e.g. GWP and acidification potential). Slightly higher variations are observed in scenario B.2 for impact categories mainly influenced by the manufacturing phase (e.g. abiotic depletion potential). This sensitivity analysis confirms the considerations discussed and demonstrates that they are not influenced by the assumptions related to factor $P_{RE,i}$.

5.3. Applications of the method and future developments

The method presented in this paper is, in the authors' view, a suitable analytical tool for making quantitative comparisons of the potential environmental impacts of new and reused and/or remanufactured products, in particular ErPs. This kind of analysis would therefore be of interest to various stakeholders, such as manufacturers, repairers and policymakers, enabling them to choose the most suitable option (between new and reused and/or remanufactured products) in environmental terms.

Regarding its application to policy development, the method is very timely, especially as the interest in the circular economy continues to grow, and reuse is becoming an effective way of maintaining a product's economic value for longer. From this point of view, policymakers are quite often confronted with questions such as “Is it actually worth promoting the reuse and remanufacturing of a certain product?”; “What are the specific components for which remanufacturing and reuse should be prioritised?”; and “How can the possible benefits from reuse be quantified from a life-cycle perspective?”. The method detailed in this paper aims to answer these questions. The case study presented gives a useful

Table 10
Environmental assessment of remanufacturing scenarios (B.1 and B.2), taking into account different values of the impacts from remanufacturing processes (P_{RE}).

		Remanufacturing scenario					
		B.1: reused HDDs and memory cards			B.2: reused HDDs, memory cards, CPU, mainboard		
		$P_{RE} = 0.5\%$	$P_{RE} = 0.2\%$	$P_{RE} = 10\%$	$P_{RE} = 0.5\%$	$P_{RE} = 0.2\%$	$P_{RE} = 10\%$
		δ					
Abiotic depletion potential (elements)	[kg Sb-eq.]	24.51	24.58	22.27	80.74	80.98	73.13
Acidification midpoint	[Mole H+ eq.]	1.17	1.17	1.15	1.48	1.48	1.44
GWP	[kg CO_2-eq.]	1.07	1.07	1.06	1.20	1.20	1.18
Ecotoxicity: freshwater	[CTUe]	1.92	1.92	1.83	12.00	12.03	10.95
Eutrophication: freshwater	[kg P eq]	1.23	1.23	1.21	4.40	4.41	4.08
Eutrophication: marine	[kg N-eq.]	1.05	1.05	1.05	1.17	1.17	1.15
Eutrophication: terrestrial	[Mole N eq.]	1.14	1.14	1.12	1.37	1.37	1.33
Human toxicity, cancer effects	[CTUh]	2.52	2.53	2.38	5.69	5.70	5.24
Human toxicity, non-cancer effects	[CTUh]	1.27	1.27	1.24	1.98	1.98	1.89
Ionising radiation	[kBq U235 eq]	1.01	1.01	1.01	1.02	1.03	1.02
Ozone depletion	[kg CFC-11 eq]	1.31	1.31	1.28	1.40	1.40	1.36
Particulate matter	[kg PM2,5-eq.]	1.3	1.3	1.3	2.0	2.0	1.9
Photochemical ozone	[kg NMVOC]	1.14	1.14	1.13	1.38	1.39	1.35
Primary energy (fossil + renewable)	[MJ]	1.05	1.05	1.04	1.14	1.14	1.13
Resource depletion (water)	[m^3 eq.]	1.05	1.05	1.05	1.16	1.16	1.14

example of the method's practical application in policymaking, namely in the framework of implementing the “Ecodesign” Directive, which concerns the formulation of material efficiency requirements.

When discussing the reuse and remanufacturing of servers, as well as many other ErPs, a common question relates to whether or not reusing components to extend a product's life reduces potential environmental impacts (for instance the GWP), compared with a newly manufactured product, particularly during the use phase. The results of the case study clearly show that reusing HDDs and memory cards is environmentally beneficial when the remanufactured server (product B) consumes 7% more energy than the newly manufactured product (product B) (i.e. the product without reused components). As illustrated, the method proposed allows the trade-offs to be quantified, for instance regarding energy consumption. This conclusion could lead to the formulation of a potential “Ecodesign requirement”, which would limit the energy consumption (E_{TEC}) of servers reusing HDDs and memory cards to a value no higher than "$\delta_j \bullet E_{TEC}$", where $\delta_j = 1.07$. The feasibility of a limit on the energy consumed by remanufactured servers was analysed as part of the “Ecodesign” preparatory study's activities on servers. Although the rationale for this type of requirement is built, as previously shown, on robust methodological foundations, it has not yet been formally proposed as a requirement of a potential regulation under the “Ecodesign” Directive, for two main reasons: the lack, to date, of a standardised methodology (Polverini and Tosoratti, 2018) for defining servers' energy consumption (E_{TEC}), and issues related to the enforceability of such a requirement (any authority in charge of enforcing the “Ecodesign” Directive should be able to verify the presence of reused components, and this is not currently the case). However, this example clearly shows how the methods and tools that support the policy analysis can provide policymakers with potential solutions that can be discussed with and enriched by stakeholders in light of all “boundary conditions”, including potential technical barriers and economic convenience.

Further analysis of Table 8 (in particular of the values of δ) shows that, in addition to the GWP environmental impact, there are impacts for which the environmental benefits of remanufacturing are outstanding, i.e. those that have been highlighted in bold. These elements provide a convincing quantitative basis for showing that remanufactured servers, according to the scenarios we considered, are environmentally effective. Therefore, policy measures aimed at addressing the environmental impact of servers should incorporate provisions for remanufactured servers. This was also done for the case study in this article by formulating potential “Ecodesign” requirements aiming to increase the share or remanufactured products. To this extent, Talens Peiró and Ardente (2015) suggested that, for the components that are most frequently reused in remanufactured servers (such as memory cards and HDDs), it should be compulsory that they can be 'identified, accessible and removable by hand or with commonly available tools'. Moreover, the suggested that it should be compulsory for manufacturers to provide repair and reuse operators with specific technical documentation for a server, such as exploded diagrams and the sequence of disassembly (Talens Peiró and Ardente, 2015). The objective of these requirements is to stimulate manufacturers to implement a “design for disassembly” of a selected list of components, which, together with the aforementioned technical documentation, should help third parties, such as repair and reuse centres, to access the selected components and disassemble them for checking, repair and/or replacement. Requirements based on this proposal are currently being hypothesised and discussed with stakeholders in the context of the “Ecodesign” initiative on enterprise servers, and the supporting analyses of this article and of the study by Talens Peiró and Ardente (2015) will provide policymakers with the necessary technical background.

The method presented in this paper could be a supporting tool not only for “Ecodesign preparatory studies”, as just discussed, but also in the related field of standardisation. The current mandate (EC, 2015b) to develop standards on material efficiency aspects explicitly predicts the definition of parameters and methods for reusing and remanufacturing products. The method presented in this paper could therefore represent an analytical reference tool for assessing the environmental impacts linked to reuse and remanufacturing.

Further research work could focus on analysing different examples of remanufactured products, including collecting additional data about remanufacturing operations. This could allow for better estimates of the impacts of remanufacturing (represented by the term “P_{RE}” in previous equations). The research could also address the comparison of potential benefits of remanufacturing products with different technological cycles (i.e. products subject to frequent changes because of technological innovations compared with products less affected by technology changes during the same time). In particular, examples of remanufactured products have so far been reported for business-to-business products. Researchers should investigate the potential benefits of reusing and remanufacturing consumer appliances.

Similar methods could be developed for other types of reuse, for example for assessing preparation for reuse (i.e. when waste products are fully, or partially, reused for the same purpose) and repurposed products reused for a different application from that originally planned (e.g. electrical vehicle batteries reused in stand-alone photovoltaic plants). The method proposed could also be integrated into REAPro (Ardente and Mathieux, 2014a, b) to assess the material efficiency of products based on several criteria (i.e. recyclability, recycled content, content of hazardous substances and valuable resources, durability) by adding a new criterion on the assessment of product's remanufacturing.

Finally, the method proposed assumes that components were reused once. The possibility of reusing components more than once is not excluded, especially for those that have a lifetime much longer than the average life of the product (e.g. frames and casings in modular products). The modelling of such a situation would imply a change in the system boundaries of Fig. 1 and would include various life cycles of different products. This could be included in the future development of the method. During the study, we did not find evidence in relation to the reuse of components more than once. However, multiple reuse could occur, for example for different products (e.g. photocopiers) (Kerra and Ryana, 2001), especially when the product is under lease, with the manufacturer retaining ownership.

6. Conclusions

The analysis of the literature and legislation demonstrated that terms related to the different types of reuse are sometimes confused or used synonymously. A first outcome of the article is the provision of an original classification for the different types of reuse. Such a classification is a first attempt to clarify the diverse definitions available and aims to contribute to the clarity of future discussions on this topic.

Subsequently, the article introduced a method specifically tailored to the environmental assessment of a remanufactured ErP. Compared with previous studies, this method includes three novel elements. First, the method proposed is comprehensive, as it includes an assessment of all life-cycle stages of a remanufactured product compared with a newly manufactured one. In particular, the method is based on an analysis of the potential trade-offs between lower environmental impacts during certain phases (for example manufacture and EoL) versus changes in energy consumption during the use phase. Second, the method is systematic, as it uses specific parameters to model influential aspects, such as energy consumption during the use phase and the impacts of remanufacturing, which are generally difficult to assess. This allows the method to be applied in the early stages of the design process, when several aspects of the product life cycle have not yet been defined. The assessment was then followed by a sensitivity analysis that allowed an understanding of how the results are affected when the parameters change. Finally, the method is general and applicable to different types of products. This is particularly relevant, as it means that the method can potentially be used in the development of policies and/or standards.

As discussed in section 2, the method to assess remanufacturing could be integrated into REAPro. Further developments could relate to analysing other reuse situations, such as preparation for reuse or repurposing.

Applying the method to the case study showed that reusing certain components (such as HDDs and memory cards) can reduce the overall life-cycle GWP (i.e. GWP indicator) even if the remanufactured product consumes more energy during operation (up to 7% more). Environmental benefits are greater for the environmental impact categories more influenced by the manufacturing stage, such as human toxicity, ecotoxicity and resource depletion. In the server example, the environmental benefits increased as the number of reused components in the product increased, as long as the energy consumption of the remanufactured server did not exceed 7% of the new one.

The method, therefore, could enable policymakers to balance several complementary policy objectives, such as global warming mitigation (related to the Paris Agreement) and implementing the circular economy (related to the EU Circular Economy Action Plan (EC, 2015a)), as well as some possible conflicting aspects, for instance using older products with lower energy efficiency can lead to greater CO_2 savings. Several OEMs already have systems in place for reusing components and remanufacturing servers. Reusing components has proven to be an effective and economic way to provide products that meet customer demand, and keep the value of the products in the economy for longer.

The method illustrated in this article was used to complement the analysis performed during the European “Ecodesign preparatory study” on servers, to develop “Ecodesign” measures in line with EU Directive 2009/125/EC. In particular, the outcomes of the case study provide policymakers with scientific evidence of the convenience of reusing servers and the need for action to promote reuse. Based on the results of the case study, measures to promote reuse (e.g. by designing to allow the disassembly of certain components to facilitate their extraction and subsequent reuse) have been proposed. This example clearly shows how the method proposed can support policymakers in identifying potentially useful policy measures, which in any case have to be analysed and enhanced by different stakeholders in light of all “boundary conditions”, including potential technical barriers and economic convenience.

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