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Review

Methodological issues in life cycle assessment for remanufactured products: a critical review of existing studies and an illustrative case study

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ABSTRACT

Remanufacturing is an important strategy in the manufacturing industry. A life cycle assessment (LCA) is often used to measure whether, and to what extent, a remanufactured product is 'better' for the environment than a newly produced equivalent. In order to obtain valid and meaningful outcomes, LCA standards and guidelines need to be followed. However, for the system boundaries selection in the LCA for remanufacturing the standards and guidelines offer insufficient guidance to practitioners. This paper reports on a literature review conducted to analyze how the first step in the LCA, i.e., the goal and scope definition stage, is shaped in prior LCAs for remanufactured products. The review suggests that the goal and scope definitions are often shrouded in obscurity in prior LCAs for remanufactured products. Moreover, different perspectives that shape the goal and scope definitions are identified and their meanings and assumptions analyzed. An illustrative case study of a real-life remanufactured product demonstrates how different perspectives in the goal and scope definition stage lead to different LCA models and different LCA outcomes. The paper concludes with several recommendations on how to shape the LCA for remanufactured products.

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1. Introduction

Remanufacturing is the process of bringing a used product back to at least its original performance with a warranty to match an equivalent new product (King et al., 2006). The cost benefits and environmental advantages of remanufacturing have made it an important strategy in many industries (Hatcher et al., 2013; Kumar and Putnam, 2008; Lund, 1984; Webster and Mitra, 2007). Moreover, end-of-life and waste management regulations, such as European Directive 2008/98/EC (European Union, 2008), and recent sustainability approaches such as Cradle-to-Cradle design (Braungart and McDonough, 2002) and the Circular Economy (Ellen MacArthur Foundation, 2013) promote the implementation of remanufacturing over other waste management strategies such as recovery and disposal.

Whether, and to what extent, a remanufactured product is better for the environment can be assessed with a life cycle assessment or LCA (Plevin et al., 2014). LCA outcomes can be used in a wide range of decisions and applications, such as, in marketing information, product selection, design decisions, or strategic planning (Weidema et al., 2004). However, the LCA for remanufactured products is controversial. An important modeling choice in preparing the LCA for a remanufactured product is whether or not to take into account the environmental burdens of the original product. Different perspectives are adopted in prior LCAs. For example, in an LCA for a remanufactured air compressor, Biswas et al. (2013) do not consider the environmental burdens of the original air compressor. Their results show that a remanufactured air compressor leads to a 96% reduction in carbon emissions in comparison to its newly manufactured equivalent. Zanghelini et al. (2014) also conduct an LCA for a remanufactured air compressor, yet they do take into account the environmental impacts of the original air compressor in the LCA. Zanghelini et al. find a 46% environmental improvement for remanufacturing. Which one of these two results is correct, if any?

LCA standards and guidelines are available to guide practitioners in conducting LCAs (Guinée, 2002; ISO 14040, 2006; ISO 14044, 2006; Weidema et al., 2004). Nonetheless, there are no specific standards, guidelines or illustrations available for remanufactured products. LCA practitioners have to rely on the general LCA guidelines, and on the (modeling) choices made by others in prior LCAs in the literature. The lack of specific guidelines can lead to a variety of perspectives in shaping the LCA for remanufactured products, as illustrated in the example of the two remanufactured air compressor LCAs. Therefore, the aim of this paper is to understand how to shape the LCA for remanufactured products.

To pursue this aim, the paper begins with an overview of those LCA guidelines and insights that are relevant for remanufacturing. Subsequently, a literature review is conducted to understand how practitioners have shaped the LCA for remanufacturing in prior studies. A first finding is that the general LCA standards and guidelines are often poorly applied in prior LCAs for remanufacturing. Moreover, the literature review shows that different perspectives are adopted in shaping the LCA for remanufactured products. Provided is an interpretation of each perspective that can be used as template in future studies. In order to illustrate the implications of the various perspectives identified, an LCA of a real-life remanufactured product is presented as a case study. Furthermore, both the literature review and the case study provide insights for practitioners as to why adhering to the general LCA standards and guidelines is important in the case of remanufacturing. Finally, conclusions are drawn and several recommendations made. Hereby, this paper aims to help LCA practitioners steer clear of current methodological difficulties in undertaking an LCA for remanufacturing.

The following research questions guide the research:

1) What LCA guidelines and recommendations are relevant for shaping the LCA for remanufactured products?
2) What perspectives can be identified in existing studies that shape the LCAs for remanufacturing and how are these motivated?
3) What are the consequences of each perspective for the LCA model, the LCA results and the interpretation of the LCA results?
4) What recommendations can be made for practitioners?

The paper is organized as follows. First, a brief overview of the goal and scope definition stage of an LCA is provided with an emphasis on the elements relevant for remanufactured products. Subsequently, the literature review methodology is presented in Section 2, followed by the results of the literature review in Section 3.1. Section 3.2 presents the illustrative case study and Section 4 provides the recommendations and conclusions.

1.1. LCA methodology: goal and scope definition

Carrying out a life cycle assessment (LCA) is the mainstream approach to assessing the environmental performance of products and processes (Plevin et al., 2014). An LCA assesses the environmental impacts associated with a product system's life cycle (Matos and Hall, 2007). ISO standards and LCA methodologies systematically guide practitioners in designing LCAs (Guinée, 2002; ISO 14040, 2006; ISO 14044, 2006; Weidema et al., 2004). ISO 14040 (2006) and ISO 14044 (2006) prescribe four stages in conducting an LCA: 1) Goal and scope definition, 2) Inventory analysis (LCI), 3) Impact assessment (LCIA), and 4) Interpretation.

This paper focuses on the perspectives that can be adopted in the goal and scope definition stage of an LCA for remanufactured products. Decisions made in this first stage determine the LCA model and therefore the ultimate outcomes of the LCA and the meaning of those outcomes (Reap et al., 2008). More information and guidelines on the other LCA stages can be found in the above ISO standards. For issues and uncertainties related to the other stages in LCA, such as data inaccuracies, data gaps, model uncertainty, and variability, see, for example, Reap et al. (2008), Ross et al. (2002), Björklund (2002), and Lloyd and Ries (2007).

The goal and scope definition stage determines the description of the product system in terms of the system boundaries and a functional unit (Rebitzer et al., 2004). In addition to the functional unit, this phase also defines impact categories, assumptions, limitations, and system boundaries. Three interrelated steps can be discerned within this stage (Reap et al., 2008; Weidema et al., 2004): 1) determining the goal and scope of the study, 2) providing a quantified reference, and 3) ensuring equivalence of systems (see Fig. 1).

Setting the goal and scope of the LCA involves “stating and justifying the goal of the LCA, explaining the goal (aim or objective)

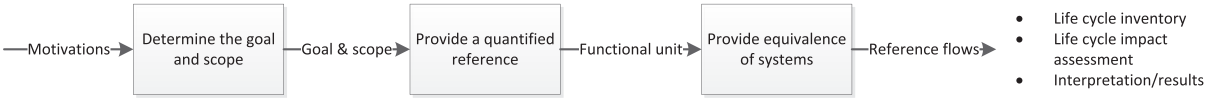

Fig. 1. Steps in the goal and scope stage of an LCA.

of the study and specifying the intended use of the results (application), the initiator (and commissioner) of the study, the practitioner, the stakeholders and the intended users of the study results (target audience)" (Guinée, 2002, p. 34). An LCA can be used for various purposes, such as hot-spot identification, product declarations and eco-labeling, supporting supplier choice, providing marketing information, choosing between alternative product systems, product development, and strategic planning and legislation (Guinée, 2002; Weidema et al., 2004, 1999).

The scope determines "the main characteristics of an intended LCA, covering such issues as temporal, geographical and technology coverage" (Guinée, 2002, p. 35). The scope can vary depending on the purpose. For example, for a customer choosing a product supplier, a short-to medium-term time horizon with a specific scope (i.e., specific product systems) typically suffices, whereas for studies aimed at reviewing cleaner production strategies for policymaking purposes, a long-term horizon with a broad coverage of solutions should be chosen (Weidema et al., 2004).

As the second step, a quantified reference is provided in terms of a functional unit (FU). The FU is "a quantified description of the performance of the product systems, for use as a reference unit" (Weidema et al., 2004, p. 13) and forms the baseline for comparing product substitutions (Guinée, 2002). In general, the FU is not simply a product or quantities of materials but related to the function or performance of the product (Reap et al., 2008) and requires three elements: 1) the magnitude of the service, 2) the duration of the service including the product's lifespan, and 3) the expected quality (Cooper, 2003). For instance, rather than the FU being "a high-capacity slurry pump", one should formulate the FU as "transporting one cubic meter of mining slurry per second over 100 km for 10 years without any spillages". However, when comparing two or more similar products, such as comparing a specific remanufactured product with its newly manufactured equivalent, it is argued that "the [LCA] procedure may be followed less stringently" (Weidema et al., 2004, p. 11). Accordingly, a product-based FU (e.g. "the FU is a high-capacity slurry pump") could be appropriate in certain situations.

In the third step, reference flows (RFs) are determined to ensure equivalence. The RF is "a quantified amount of product(s), including product parts, necessary for a specific product system to deliver the performance described by the functional unit" (Weidema et al., 2004, p. 13). The RF should ensure equivalence between alternative product systems included in a comparative study (Guinée, 2002). For example, returning to the mining example above, the slurry could be transported with x slurry pumps and 100 km of piping, or with y trucks driving 100 km several times per day over a newly constructed road. Depending on the goal and scope and FU of the LCA, the RF of a remanufactured product system may include a) materials and processes for the original product, and/or b) materials and processes for multiple remanufacturing cycles. This decision is known as the system boundaries selection (ISO 14044, 2006, clause 4.2.3.3.1).

1.2. System boundaries selection and allocation

According to the ISO 14044 (2006) standard "the selection of the system boundary shall be consistent with the goal of the study" (4.2.3.3.1, p. 8). Except for this, there are no other guidelines on how to determine the system boundaries for a remanufactured product. Although remanufacturing is essentially a form of closed-loop recycling (King et al., 2006), a similar type of selection problem can be found in open-loop materials recycling literature (Atherton, 2007; Ekvall and Tillman, 1997; Frischknecht, 2010). In open-loop recycling, materials from one product system are recycled a different product system (ISO 14044, 2006). The system boundaries selection problem in open-loop materials recycling is whether the environmental burdens of the first use of the materials are fully allocated to that initial life cycle, or whether they are allocated to future life cycles. The former approach is referred to as the *cutoff* approach, whereas the latter approach is referred to as the *avoided burden* approach (Atherton, 2007; Frischknecht, 2010).

In the cutoff approach, materials that are being used in the next or future life cycle do not bear any environmental burdens from the initial life cycle. The second use of the materials only bears the environmental impacts of collecting, cleaning, replacing, and restoring of recycled materials. The avoided burden approach assumes that recycling avoids the environmental burdens of virgin materials and production in the future. The avoided environmental impacts are therefore credited to the initial life cycle. In contrast to the cutoff approach, the avoided burden approach shifts the environmental burden into the future hereby 'rewarding' the initial material or product for its recyclability qualities. According to Frischknecht (2010), both approaches are ISO-compliant, but the goal of an LCA study does not determine the appropriate modeling approach. Instead Frischknecht (2010) concludes that "the way [open-loop] recycling is modelled is influenced by differences in values, views of the world and cultural perspectives" (p. 670).

In the example of the two remanufactured air compressors (see Section 1), Biswas et al. (2013) employ an approach similar to the cutoff approach. They assume that the raw material burdens of the remanufactured product are allocated to the original use of the air compressor. Only materials and processes for replacement parts and cleaning are considered in the LCA for the remanufactured air compressor. According to Biswas et al. (2013), 96% of the carbon emissions of making a new air compressor are avoided due to remanufacturing. In contrast, Zanghelini et al. (2014) expand the system boundaries by considering the environmental burdens of both the original product as well as the remanufactured product in the LCA. The environmental burdens are distributed over the new air compressor and the remanufactured air compressor. According to Zanghelini et al. (2014), remanufacturing avoids 46% in carbon emissions in comparison to a product system with only newly manufactured air compressors.

The question remains whether one of these approaches is the right one, if any. Existing LCA standards and guidelines offer limited guidance on this issue, except that it should be consistent with the goal of the study. It may be possible that the LCA goal does not determine which approach should be taken, like in open-loop materials recycling. As the next step in the clarification of this, a literature review is presented that assesses the goals, motivations and approaches used in shaping the goal and definition stage in prior LCAs for remanufacturing.

2. Method

Fink (1998) defines a literature review as "a systematic, explicit, and reproducible design for identifying, evaluating, and interpreting the existing body of recorded documents" (p. 3). A literature review can serve various purposes in research (Hart, 1998). The aim of this literature review is to identify the perspectives that have been used in shaping the goal and scope definitions of LCAs for remanufacturing and to grasp the logic behind each perspective. As a result, an image is created of the methodological content of the field, against which the results of existing studies can be judged.

2.1. Selection of articles and delimitations

The review aimed to cover English-language papers in peer-reviewed scientific journals. The literature search was based on a topic search (keywords: "remanufacturing", "remanufactured", "LCA", "life cycle assessment", "environmental performance") using Google Scholar (scholar.google.com) and Web of Knowledge (www.webofscience.com) as the primary library services. A quick content analysis was used to identify articles that discussed results in terms of the environmental performance, based on LCAs, of remanufactured products and only these were included in the later analysis. The selection was extended by reviewing the references of articles included after the quick content analysis (i.e., a backward search), and by using library services such as Google Scholar to identify other articles that cited the already included articles (i.e., a forward search).

2.2. Content analysis

Content analysis is a sound method to identify the perspectives that have been used in LCAs for remanufacturing. Neuendorf (2002) defines the overall goal of content analysis "as the systematic, objective, quantitative analysis of message characteristics" (p. 1). Seuring and Gold (2012) consider content analysis as an analytical tool "for conducting rigorous, systematic and reproducible literature reviews" (p. 545).

As the first step in the content analysis, descriptives, such as publication outlet, year of publication, and type of product studied, were noted. Subsequently, the goal and scope definitions were examined. The three steps in the LCA goal and scope definition stage (see Fig. 1) formed the backbone of the content analysis. Accordingly, the following steps were followed:

1) The initial motivation and objectives of each reported LCA were reviewed. All the relevant statements concerning the initial motivation and objectives included in each article were extracted and patterns in the motivations and objectives were identified.
2) The goals of the LCA studied in each article were reviewed and checked against the standard requirements, including the intended use of the application and the target audience.
3) The functional unit (FU) of each LCA was reviewed in terms of four elements: a) whether the FU was described as a function/service or as a specific product, b) the scale of the function/service/product, c) the duration or lifespan of the function/service/product, and d) the expected level of quality.
4) The reference flows (RFs) were reviewed for three elements: a) whether the RF used in the LCA for a remanufactured product system included the materials and processes for the newly manufactured product, b) the (potential) number of remanufacturing cycles per product, and c) whether an analysis was conducted for the environmental performance of a varying number of remanufacturing cycles (i.e., one cycle, two cycles, etc.).
5) The possible exclusion of certain life cycle stages from the LCA was analyzed for each article.
6) The reported LCA results were collected. LCA results presented in the abstract and/or conclusion sections of each article were taken as the main findings. If these sections did not report any LCA results or conclusions, the results section was consulted.

2.3. Rigor of the content analysis

Rigor and transparency are key to ensuring and increasing both the validity and reliability of the content analysis (Lincoln and Guba, 1985; Shank, 2006). To this end, an overview of relevant quotes from reviewed articles used in the content analysis is included in Appendix A. Further, selected quotes from the reviewed articles are used in the results section to support and illustrate the author's classifications and conclusions.

3. Results and discussion

3.1. Literature review

A more detailed summary of the literature review findings can be found in the appendices. Appendix A focuses on the source material, i.e., selected quotes, and Appendix B provides the results of the content analysis.

3.1.1. Literature review: results

The body of literature identified comprises 13 articles. The breakdown by date of the publications reviewed is shown in Fig. 2. Most of the articles (9 out of 13) have been published in the past five years. Five of the articles were published in conference proceedings (see Fig. 3a). The Journal of Cleaner Production and the Journal of Remanufacturing have each published three articles addressing LCAs for remanufactured products, and the Journal of Industrial Ecology has published two (see Fig. 3a). On the whole, the products can be characterized as complex, (electro-) mechanical durable goods (see Fig. 3b). A notable exception being a toner cartridge reported in Lindahl et al. (2006).

With only 13 articles identified for the literature review, it can be concluded that LCAs for remanufacturing still form a niche in the LCA literature. Given the growing body of environmental regulations, and new industrial paradigms such as the Circular Economy, one can expect more studies on the use of LCA in remanufacturing. This upward trend is reflected in the fact that most of the published articles have been published in the past five years (see Fig. 2). Also there may be a much larger number of LCAs that are undertaken in industry but never formally published.

The articles on LCAs for remanufacturing provide incomplete information on the exact goals of the LCA (Fig. 3c). The primary goal as stated in the articles is to compare the environmental performance of a remanufactured product to a newly manufactured equivalent but details concerning the intended use of the results and the intended users of the study (i.e., the target audience) are sketchy. For instance, Liu et al. (2014) note that "an LCA can help decision makers select the product or process that results in the least impact to the environment" (p. 569), but it is not explained who the decision-makers are and what the intended type of application exactly is. However, six papers do state that a secondary goal is to support decision-making in product design and/or remanufacturing systems management. Through such statements, the intended use of the results and the target audience can often be inferred.

Second, four articles describe the function or service in the FU (i.e., function-based FU, see Fig. 3d). Three of these articles provide full details of the FU according to LCA standards by stating the magnitude of the function, and its duration/life span. For instance, in the article by Kerr and Ryan (2001), the FU is given as: "12 million copies are produced over a maximum period of ten years" (p. 78). Most articles however refer to the product in the FU, rather than the function or service that the product performs (i.e., product-based FU). For instance, Warsen et al. (2011) state the FU as: "the manufacture of a type MQ250 transmission" (p. 68). Three articles do not

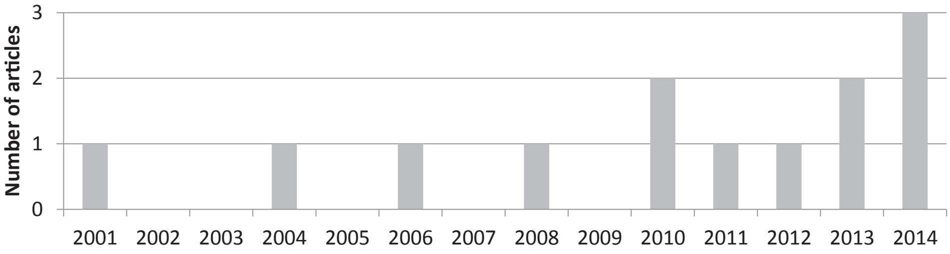

Fig. 2. Distribution of articles per year ($N = 13$).

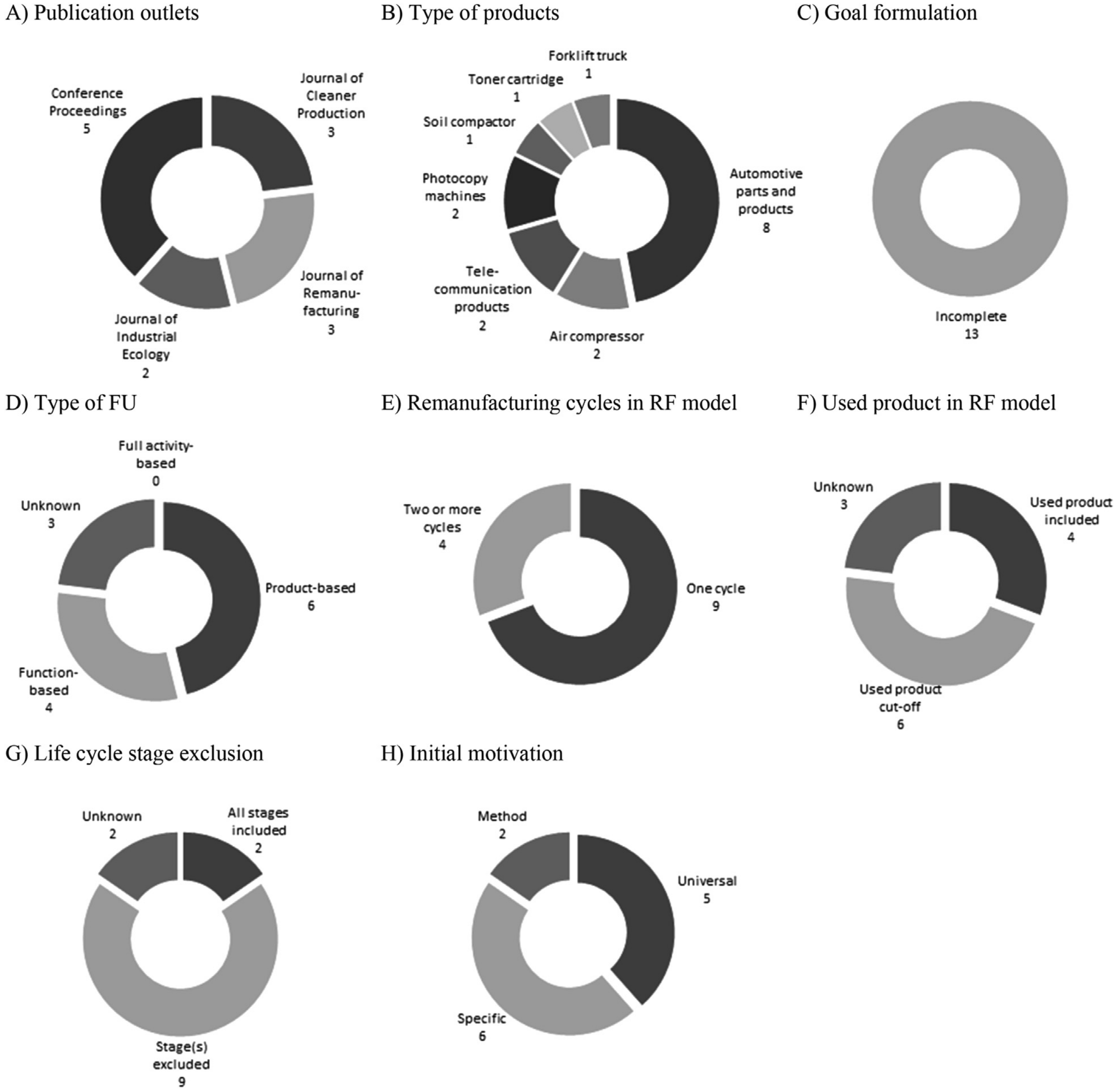

Fig. 3. Descriptive results of the literature review ($N = 13$).

formulate an FU. Further, none of the articles consider the function of the newly manufactured product or a remanufactured product in the service(s) or process(es) in which the product is used (i.e., a full activity-based FU). For instance, none of the articles that concentrate on automotive parts or products include the activity of transporting goods from A to B as the basis for their FUs. In terms of describing the expected level of quality in the FU, all the articles explain that the quality of the service or product provided by the remanufactured product system was assumed similar to that of a newly manufactured alternative. One could argue here that this is inherent to the definition of remanufacturing, namely: remanufacturing is the process of bringing a used product *to at least* *original performance with an equal warranty as an equivalent new product* (King et al., 2006).

Third, the majority of articles assess products with one remanufacturing cycle (Fig. 3e). In addition, three articles fail to adequately detail the RFs (Fig. 3f). In four articles, the RFs of the remanufactured product systems include materials and processes of the newly manufactured product, whereas six articles exclude the newly manufactured product from the remanufactured products system (i.e., cutoff). Finally, while two articles include all the life cycle stages in the LCA, nine articles omitted the use stage, and from the remaining two articles it could not be determined whether all stages were included (see Fig. 3g).

In order to review the consistency between the goal and scope definition and the LCA's starting points, the initial motivation for each assessment is now discussed. Three types of motivations were identified.

The first type of motivation, labeled as ‘universal’, was identified in five papers (see Fig. 3h). These articles start with the observation that although remanufacturing has become an important manufacturing strategy, hard facts about the environmental benefits of remanufacturing are still lacking. The initial motivation of this group of articles was to acquire an understanding of the *general* environmental benefits of remanufacturing. For instance, Kerr and Ryan (2001) state: “to date, surprisingly few other studies have attempted to quantify the environmental benefits of remanufacturing, and none of these takes into account the entire product life cycle. This study was an attempt to begin filling this gap in knowledge by quantifying the overall life cycle environmental benefits of remanufacturing” (pp. 76–77). Another example of this type of motivation can be found in Lindahl et al. (2006) who state: “this paper aims at identifying general environmental pros and cons with remanufacturing. The aim is to do so by using different existing, practical examples of remanufacturing industries” (p. 195).

The second type of motivation, labeled as ‘specific’, was found in six articles. These articles concentrate on the environmental benefits of a specific remanufactured product. In contrast to articles with a ‘universal’ motivation, these articles do not aim to generalize their findings beyond the remanufactured product being studied. For instance, Warsen et al. (2011) stated the goal as: “to analyze and compare the environmental impacts of a newly manufactured transmission model with a genuine remanufactured transmission of identical design” (p. 67).

Finally, two articles state their primary purpose as proposing a methodology for assessing the environmental performance of a remanufactured product. To demonstrate and evaluate the proposed method, specific remanufactured product systems are used as case studies.

3.1.2. Literature review discussion: perspectives, consequences and consistency

The results of the literature review reflect a fragmented landscape. Many types of motivation, goal definitions, FU formulations, and reference models can be found in existing LCAs for remanufactured products. Goal statements, especially the intended application and the target audience, are often incomplete. Although LCA standards allow non-standard FUs in certain types of assessments (see Section 1.1), it is emphasized that this should not be at the expense of the clarity and validity of the LCA.

All the reviewed articles report their LCA results and conclusions in a homogeneous way, and without raising any methodological limitations (see Appendix A). In order to interpret the results of the LCAs, and to fill in blanks such as the intended application and the target audience, the aims, the scope, the FU and the RF models were examined and compared. Eight articles provided sufficient details in the goal and scope definition to infer missing elements and review the meaning. Based on the analysis of these articles, two types of perspectives, the ‘supporter’ perspective and the ‘neutral’ perspective, emerged, and these will be explained next.

In six articles, the FU and RFs have relatively short time horizons (i.e., a single product life cycle), and are restricted to a single specific product system or one with only a few alternatives. An approach similar to the cutoff approach in open-loop materials recycling (see Section 1.2) is applied. In addition, these articles omit the use stage from the LCA, and some articles also omit the end-of-life stage. One way to interpret these articles is through the lens of a supporter of remanufacturing. The ‘supporter’ aims to highlight the environmental benefits of a remanufactured product, using LCA as vehicle. Adopting short time horizons and restricted FUs and reference models usually yield a better environmental performance for a remanufactured product than for its newly manufactured alternative (as will be demonstrated in Section 3.2). Also products that are remanufactured oftentimes have a long operational timespan, and the environmental impacts generated in the use stage are usually significant. When the operational efficiencies of a remanufactured product and its newly manufactured equivalent are assumed to be similar, the use stage can be omitted. The same may apply for the end-of-life stage. Whereas the absolute environmental improvement remains unchanged when omitting the use and end-of-life stages, the relative environmental performance improves in favor of the remanufactured product (this will also be illustrated in Section 3.2).

Nevertheless, the ‘supporter’ perspective could be meaningful to an environment-conscious product user who is deciding whether to buy a remanufactured product for use in the coming years. This decision-maker is likely to only be interested in the environmental impact they can influence, i.e., by either buying a remanufactured product or a newly manufactured equivalent. The time horizon attached to the decision will equal the life of the product or may be less. It will be irrelevant to this decision-maker to what extent the remanufacturing program as a whole is beneficial, or how many times the product can be remanufactured in the longer term.

The ‘supporter’ perspective is less meaningful to others such as policymakers who want to know whether remanufacturing is a strategy worth stimulating compared to other environment-friendly production strategies, or neutral observers who are interested in the long-term environment benefits of a particular remanufactured product system. Such audiences need other types of FUs, usually with extended time horizons and numerous product or solution alternatives.

Two articles include an aim, scope, FU, and RF models with relatively long time horizons and that take into account the environmental burdens of the used product. In contrast to the ‘supporter’ articles, which employ the cutoff approach, these two articles expand the system boundaries (see Section 1.2) in order to take into account the environmental burdens of the used product. They thus seem to provide a relatively ‘neutral’ perspective in the LCA by informing audiences of the longer term environmental benefits of a remanufacturing system and how well the hybrid manufacturing–remanufacturing program performs. Even so, these two articles incorporate several optimistic assumptions, which are inevitable at a certain point. For instance, it is implicitly assumed that the RF model remains unchanged during the lengthy time frames, thereby ignoring uncertainties due to possible changes and developments in the future. A new technology may be developed that makes the environmental efficiency of the newly manufactured product superior again. Although this type of uncertainty is present in both perspectives, the ‘neutral’ perspective increases this uncertainty. Another less ‘neutral’ assumption is that each newly manufactured product can be remanufactured. If, as seems likely, some machines become unsuitable for remanufacturing, the actual environmental benefit will be lower. Similar considerations could have been added (e.g., adding a sensitivity perspective for the remanufacturing rate), which could further

Table 1
Overview of the typical properties of the two perspectives identified in the literature review.

	Supporter perspective	Neutral perspective
Identified in # articles[a]	6	2
FU time horizon	Short-term	Long-term
Number of life cycles in FU	One	Multiple
System boundaries selection method	Cutoff	System expansion
Alternatives in reference flow model	Limited	Multiple

[a] In total 13 articles were reviewed. It was however not possible to identify a perspective in five articles due to a lack of information.

increase the 'neutrality' of the LCA, but that will also introduce more and other forms of uncertainty. Table 1 summarizes the two perspectives.

Six articles that have an additional goal of providing results to help decision-making in (re)manufacturing companies are relatively clear, in terms of this sub-goal, regarding the LCA goal and scope definition. The target audience is engineers, product developers, or managers. Accordingly, these articles concentrate on different remanufacturing scenarios (e.g., the location of remanufacturing) or design alternatives (e.g., using specific materials in the newly manufactured product) in the LCA RF model. Also the LCA goal, the FU, and the RFs appear internally consistent in these articles. Nevertheless, most of these articles suffer from the problem of including different perspectives since these articles also aim to compare a remanufactured product to its newly manufactured equivalent.

Table 2 shows that LCAs that share similar initial motivations and goals still opt for different perspectives that give different outcomes. Two of the five articles labeled in this review as 'universal', i.e., having the aim of understanding the general environmental benefits of remanufacturing, applied a 'supporter' perspective (see Table 2). These two LCAs seem biased. Only Zanghelini et al. (2014) applied a 'neutral' perspective, an approach that seems more appropriate when seeking to expose the general pros and cons of remanufacturing. The two remaining 'universal' articles provide insufficient information to determine the perspective taken.

Three of the six articles reflecting a 'specific' motivation, i.e., concentrating on a specific remanufactured product system, adopted a 'supporter' perspective. An exception is the article by Goldey et al. (2010) that, despite the product-specific aim of their LCA, adopted a 'neutral' perspective. For LCAs with a 'specific' aim, both the 'supporter' and 'neutral' perspectives are appropriate. In other words, the motivation and goal of these LCAs do not determine the appropriate perspective. It is likely that the adopted perspective reflects the practitioners' "values and views of the world", as is also argued in the open-loop materials recycling debate in literature (Frischknecht, 2010). These values and views are however not explained in any of these articles. The two remaining 'specific' LCAs for remanufactured products provide insufficient information to determine the perspective taken.

Overall, the findings suggest that those active in this field are insufficiently aware of the different perspectives that can be taken in the goal and scope definition stage of LCAs for remanufactured products. As a consequence of the weaknesses in defining the goal and the scope and of the failure of recognizing different perspectives, the LCA results can be biased and open to misinterpretation. Furthermore, the goal of the LCA does not always determine which of the two perspectives is appropriate, as is the case with LCAs with a 'specific' motivation and goal.

3.2. Illustrative case study: the case of a remanufactured folder inserter

We now turn to a case study example to illustrate the perspectives found in the literature review. The product in question is the DS-63 folder inserter produced by Neopost. As with most of the products considered in the reviewed articles, the DS-63 folder inserter is a complex, durable, electro-mechanical product. This product was selected for this example because of being granted access to life cycle inventory (LCI) data and life cycle impact assessment (LCIA) results for this product. This enables one to demonstrate the consequences of selecting each of the identified perspectives for the life cycle model and the impact of this on the results. EIME software, by CODDE, was used to conduct the LCA (CODDE, 2013). However, first, the folder inserter is introduced.

3.2.1. The DS-63 folder inserter

Folder inserters are machines that are capable of automatically folding documents, inserting them into envelopes, and then closing the envelopes at high speeds and volumes (see Fig. 4). As such, the main function of folder inserters is to fold sheets of papers and insert these sheets into envelopes, and then seal them, at a specific rate and over a specific period of time. Folder inserters are used by companies operating large mailing centers. Neopost Technologies B.V., a European manufacturer of document systems, produces the DS-63 folder inserter. In the past, old folder inserters were disposed of, with some parts recycled. In 2012, Neopost started a program to remanufacture one of its models: the DS-63 folder inserter. Remanufacturing involves inspecting, cleaning and replacing parts suffering from wear and tear in the used product, Further, the remanufactured DS-63 is fitted with a new housing, a new display and a new user interface, and is thereafter labeled and sold as a Factory Produced New Model (FPNM) DS-63. In parallel, the company continues to manufacture new DS-63 folder inserters, in this article identified as the NEW DS-63.

3.2.2. Goal and scope stage

Whereas the goal of the LCA for remanufacturing is generally to compare and investigate the differences between a newly

Table 2
Overview of reviewed articles: type of motivation versus type of perspective, and an indication whether or not the type of motivation and type of perspective in the articles match.

Type of motivation/objective	Neutral perspective	Supporter perspective	Unknown perspective (due to a lack of info)
Universal	Match: Yes • Zanghelini et al. (2014)	Match: No • Biswas et al. (2013) • Kerr and Ryan (2001)	Match: Unknown • Fatimah et al. (2013) • Lindahl et al. (2006)
Specific	Match: Yes • Goldey et al. (2010)	Match: Yes • Liu et al. (2014) • Warsen et al. (2011) • Smith and Keoleian (2004)	Match: Unknown • Sutherland et al. (2008) • Lindahl et al. (2014)
Method	–	Match: Yes • Schau et al. (2012)	Match: Unknown • Amaya et al. (2010)

Fig. 4. DS-63 folder inserter.

Table 3
Goals for the illustrative LCA case study.

Perspective(s)	Goal	Goal description	Target audience
Supporter perspective	GOAL-1	To analyze the environmental benefits of using a remanufactured folder inserter compared to newly manufactured equipment. The results can be used to decide whether or not to buy or lease a remanufactured product or a newly manufactured product.	Product user (purchase department/ management)
Neutral perspective	GOAL-2	To analyze the environmental benefits of a remanufactured folder inserter in a hybrid new manufacture–remanufacturing system compared to a purely new manufacturing system. The results can be used to substantiate any claim about the effectiveness of remanufacturing folder inserters in a hybrid new manufacture –remanufacturing system.	Neutral observer

manufactured and a remanufactured product, the goal of the present study is to investigate the effect of, often implicit, decisions on the outcome of such a comparison. This case study compares and illustrates the ‘supporter’ and the ‘neutral’ perspectives. Appendix C introduces and illustrates two additional alternative perspectives (i.e., the ‘full activity’ and ‘factory’ perspectives), which were not found in the literature review but may be of interest to LCA practitioners and other interested readers.

Table 3 lists the perspectives and LCA goals that will be illustrated in this folder inserter LCA.

An FU is formulated for each perspective and goal (see Table 4). The folder inserter is designed for 900,000 folding and insertion actions during the average five-year lease period. This equates to 15,000 mail pieces being folded and inserted each month, which forms the basic building block of each FU. In addition, the RFs are specified for each FU.

GOAL-1 and FU-1 reflect the goals and FUs found in the majority of reviewed articles, i.e., a ‘supporter’ perspective and a product-based FU. The function, as defined in the FU, can be fulfilled by one new (NEW DS-63) or by one remanufactured (FPNM DS-63) machine. No other product system alternatives are assessed. GOAL-2 and FU-2 resemble the goals and FUs identified in articles with a ‘neutral’ perspective, i.e., Goldey et al. (2010) and Zanghelini et al. (2014). The scenario is as follows: the lifetime of a newly manufactured DS-63 folder inserter can be extended once by remanufacturing, doubling the resulting total lifetime to 10 years. With this possibility, FU-2 can be fulfilled with either two NEW DS-63 folder inserters, each with a lifetime of five years, or one NEW DS-63 folder inserter, with its lifetime extended to 10 years through remanufacturing (a “NEW-FPNM” DS-63). The option of FU-2 being served by two (remanufactured) FPNM DS-63 folder inserters, each with a lifetime of five years, is not considered as this would contradict the proposed hybrid new manufacture–remanufacture system stipulated in GOAL-2.

Table 4
Definitions of functional units and reference flows in the illustrative LCA case study.

Type of perspective	FU No.	Definition of FU	RFs
Supporter perspective	FU-1	Fold and insert 15,000 mail pieces per month for five years using a DS-63 folder inserter	• Materials and activities for one NEW DS-63 • Materials and activities for one FPNM DS-63
Neutral perspective	FU-2	Fold and insert 15,000 mail pieces per month for ten years	• Materials and activities for two NEW DS-63 machines • Materials and activities for one ‘NEW-FPNM’ DS-63

3.2.3. Life cycle inventory (LCI) stage

For each FU, a life cycle inventory is established. Table 5 displays the LCI elements for FU-1 and FU-2. The LCI for FU-2 is a variation of the LCI for FU-1 and can be obtained through additions to and multiplications of FU-1.

For FU-1, the following flows and processes are taken into account in the life cycle for the NEW DS-63 and FPNM DS-63: raw materials and parts, upstream transport of raw materials and parts, manufacturing and/or remanufacturing processes, packaging, energy consumption during the usage stage, maintenance, recycling and disposal processes (based on the WEEE end-of-life scenario), transport to the customer, and transport of used machines to the factory for remanufacturing. Impacts of remanufacturing operations such as testing, disassembly and cleaning are assumed to have negligible impact. Details of the other sub-elements and quantities of each LCI have been omitted from this article for space reasons. Only essential data for the purpose of illustrating the various perspectives are provided.

The transportation of used DS-63 folder inserters to the factory is modeled in the end-of-life stage (a figure of 1300 km by truck is used). The WEEE end-of-life scenarios are based on the Waste Electrical and Electronic Equipment directive for the recycling and disposal of products. It includes data on pretreating used products, transportation, incineration, and landfill.

In the ‘supporter’ perspective (FU-1), the environmental burdens of the NEW DS-63, including final WEEE disposal processes in EoL, are fully allocated to the newly manufactured DS-63 folder inserter even though the product can be remanufactured, instead of being recycled and landfilled (see Table 5). As a result, the used NEW DS-63 that is remanufactured into an FPNM DS-63 comes without any environmental burdens. Therefore, only impacts related to the replacement parts are taken into account in the raw materials, manufacturing, and end-of-life stages of the FPNM DS-63. With regard to the final disposal of the FPNM DS-63, only the impacts for disposing the replaced parts are included in the RFs of FU-1. Conversely, the RFs change in the ‘neutral’ perspective (see FU-2 in Table 5). The ‘NEW-FPNM’ DS-63's RFs include both processes and materials of the newly manufactured folder inserter as well as processes and materials for the remanufactured folder inserter.

3.2.4. Life cycle impact assessment (LCIA) stage and discussion

The reviewed articles use a range of output eco-indicators in their life cycle impact assessments (LCIAs). As a general rule, the choice made will not radically effect the outcome of a comparison. The Product Environmental Profile (PEP) indicator set for electrical

Table 5
Life cycle inventory (LCI) for FU-1 and FU-2.

Functional unit	Product system	Raw materials	Manufacturing	Distribution	Use	End-of-life & reverse logistics
FU-1	One NEW DS-63	- Raw materials - Upstream transport	- Manufacturing processes	- Transport to customer - Packaging	- Energy consumption - Maintenance	- WEEE scenario
	One FPNM DS-63	- Raw materials for replacement parts - Upstream transport for replacement parts	- Manufacturing processes for replacement parts	- Transport to customer - Packaging	- Energy consumption - Maintenance	- WEEE scenario for replaced parts - Return transport for used DS-63 to factory
FU-2	Two NEW DS-63s	- 2× Raw materials - 2× Upstream transport	- 2× Manufacturing processes	- 2× Transport to customer - 2× Packaging	- 2× Energy consumption - 2× Maintenance	- 2× WEEE scenario
	One 'NEW-FPNM' DS-63	- Raw materials - Upstream transport - Raw materials for replacement parts - Upstream transport for replacement parts	- Manufacturing processes - Manufacturing processes for replacement parts	- 2× Transport to customer - 2× Packaging	- 2× Energy consumption - 2× Maintenance	- WEEE scenario - WEEE scenario for replaced parts - Return transport for used DS-63 to factory

equipment was used. In the case study used in this article, the Global Warming Potential (GWP) is used, as this is a familiar eco-indicator from the PEP indicator set, which can be found in most LCAs for remanufactured products.

Table 6 shows the results of the LCIA for each FU expressed as the percentage reduction in kg CO_{2eq} (i.e. the GWP) relative to an all-new folder inserter. Both FUs show that the remanufactured (FPNM) product reduces the GWP compared to the newly produced folder inserter. The absolute benefit in terms of the GWP is the same for both FUs. However, the relative GWP benefits differ significantly depending on the FU selected and the life cycle stages included (see Fig. 5).

The case study demonstrates how different perspectives translate into different LCA goals, FUs, and RFs (see Section 3.2.2), to a different LCI (see Section 3.2.3), and lead to different results. The 'supporter' perspective (FU-1) with the exclusion of the use and distribution life cycle stages produces the highest relative environmental benefit of 47.21%. This perspective was the most common in the articles reviewed. Taking the 'neutral' perspective (FU-2), the relative advantage falls significantly to less than 23.6%, and to 11.85% when including all life cycle stages.

4. Conclusions

An important modeling choice in the LCA for remanufactured products is whether or not to take into account the environmental burdens of the original product. This decision, i.e., the system boundaries selection, is made in the goal and scope definition stage of the LCA. Multiple modeling perspectives can be found in prior LCAs. These perspectives can lead to (very) different LCA outcomes. Existing LCA standards and guidelines offer limited guidance on which modeling perspective is appropriate, except that it should be consistent with the goal of the study.

By conducting a literature review, it was evaluated how practitioners have shaped the goal and scope stage in prior LCAs for remanufacturing. Firstly, the review showed that the goal and scope stage in LCAs for remanufacturing is generally opaque. The ISO 14044 standards are clear on which information should be provided in the goal and scope definition of the LCA. But one-third of the reviewed articles failed to provide this information making it impossible to interpret the LCA result and the perspective adopted. In the remaining articles, information regarding the aim and the scope of the study was presented, although frequently incomplete, making it difficult to be sure about the meaning of the results. Although the ISO standards (ISO 14040, 2006; ISO 14044, 2006) are mentioned in most of these articles, a possibility is that practitioners are insufficiently aware of the reasons underlying these standards. In this regard, this study presents several insights and examples as to why providing the details of the goal and scope definition as required by ISO 14044 is important in the LCA of remanufactured products.

Secondly, authors have implicitly adopted two different perspectives in selecting the system boundaries. Based on an in-depth examination and comparison of the goals, functional units (FUs) and reference flows (RFs) incorporated in prior studies, two perspectives have been identified which were labeled as the 'supporter' and the 'neutral' perspectives. The majority of the articles reviewed formulate an FU and RFs that maximize the environmental benefit of remanufacturing, hence the 'supporter' (of remanufacturing) tag. The 'supporter' perspective employs the cutoff approach. This perspective adopts product-based FUs with relatively short time horizons and restricted RF models, and excludes certain life cycle stages. A minority of the articles adopted a 'neutral' perspective by expanding the system boundaries. This perspective adopts function-based FUs with relatively long time horizons, extended RF models, and sometimes includes all the life cycle stages.

The 'supporter' and 'neutral' tags have been chosen to reflect a meaningful interpretation of the perspectives taken in the reviewed articles. It is possible that in future studies, with different goals and contexts, a product-based FU with relatively short time

Table 6
Results of LCIA expressed in terms of global warming potential (in kg CO_{2eq}) for the two different perspectives and functional units.

	Alternative	Raw materials & manufacturing	Distribution	Use	End of life & reverse logistics	Total	Total without distribution and use stages	Absolute and relative difference to NEW	Absolute and relative difference to NEW (without distribution and use stages)
FU-1	One NEW DS-63	353	82	273	5	**713**	**358**	169 **23.70%** ⇩	169 **47.21%** ⇩
	One FPNM DS-63	182	82	273	7	**544**	**189**		
FU-2	Two NEW DS-63s	706	164	546	10	**1426**	**716**	169 **11.85%** ⇩	169 **23.60%** ⇩
	One 'NEW-FPNM' DS-63	535	164	546	12	**1257**	**547**		

Notes: ⇩ denotes a reduction in GWP impact due to remanufacturing.

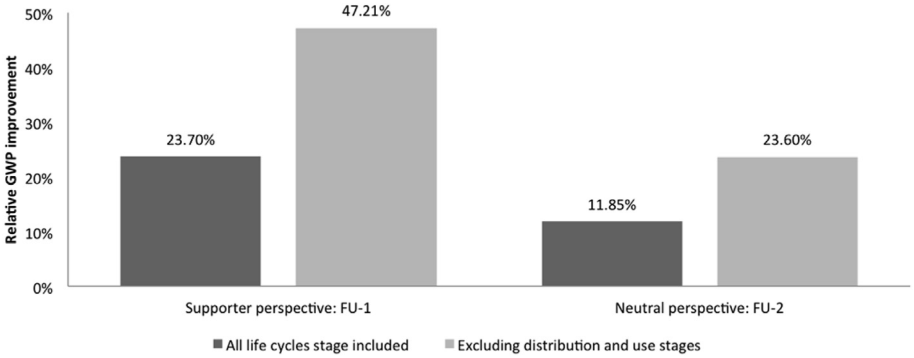

Fig. 5. Comparison of relative environmental benefits for the two different perspectives and functional units.

horizons and a restricted RF model may provide the more neutral picture, and that a function-based FU with relatively long time horizons and an extended RF model may be supportive. The combination of perspective (i.e., type of FU, shape of the RF model) and label (i.e., 'supporter' and 'neutral') used in this paper should therefore not be used as a general principle.

In theory, multiple perspectives can be appropriate, provided that the perspective is aligned with a study's initial motivations and goals (ISO 14044, 2006, clause 4.2.3.3.1). The review shows that the link between the initial motivation and the perspective adopted can sometimes be questioned. It seems that two articles are purportedly building an understanding of the *general* environmental benefits of remanufacturing while adopting the inherently favorable 'supporter' perspective. One can question if these papers provide valid results with regard to the general environmental advantages of remanufacturing. However, in several other reviewed LCAs the motivation and goals do not determine the appropriate perspective. This was exhibited in LCAs that pursued a product-specific goal and motivation. Accordingly, both perspectives have been used across these studies. It is likely that the adopted perspective reflects the practitioners' "values and views of the world", as is argued in the open-loop materials recycling literature (Atherton, 2007; Ekvall and Tillman, 1997; Frischknecht, 2010).

The two perspectives have been illustrated with a case study based around a real-life remanufactured product – the DS-63 folder inserter. The folder inserter case study demonstrates how each perspective translates into a different LCA goal, with different intended applications and target audiences, different FUs, different RF models, different life cycle inventories, and ultimately, into different outcomes. The illustrative case study results underline the importance of formulating a clear LCA goal and scope, and then matching the FUs and RF models to this.

Overall, the field appears insufficiently aware of the different perspectives that can be taken concerning the LCA for remanufacturing. Which perspective was adopted and whether it matched with the LCA goals could only be identified through an in-depth analysis because essential information on the goals and scope was often missing or unclear. Based on the findings of this study, the following recommendations are made:

1. Existing LCA methodologies (e.g., Guinée, 2002; ISO 14040, 2006; ISO 14044, 2006; Weidema et al., 2004) for the goal and scope stage of an LCA should be used in LCAs for remanufactured products. It is not sufficient to casually refer to these sources, as is exhibited in several of the articles reviewed; the recommended steps and guidelines have to be applied.
2. Practitioners should align the goal and the scope of an LCA with their initial motivation; researchers with the research questions set in their study. This article highlighted two perspectives that could be adopted in LCAs for remanufacturing programs, and highlighted the widely different consequences for the LCA model and its outcomes. When the motivation and goal of the study allow for multiple modeling perspectives, these perspectives should be compared in a sensitivity analysis according to the ISO standards (ISO 14044, 2006, clause 4.3.4.1).
3. While the 'supporter' and 'neutral' perspectives can be used as a template, other perspectives are possible (see Appendix C). As an alternative, the taxonomy proposed by Herrmann et al. (2014) could be used to determine and communicate the type of LCA and which perspectives to employ. For some purposes, such as policymaking, it has even been questioned if an attributional LCA is at all appropriate (Bento and Klotz, 2014) or that a change-based (consequential) analysis may provide more valid results (Plevin et al., 2014).
4. Practitioners should provide all the necessary details and justifications used in the goal and scope definition stage of an LCA. Ideally, similar terminology should be used as in existing LCA standards and guidelines (see recommendation #1). In particular, information concerning the intended use of the LCA results and the target audience is critical for both practitioners as well as readers of LCA reports. In addition to study's initial or general motives, these elements will determine the functional unit and the reference flow model and, therefore, determine the meaning of the LCA outcomes. Without providing these details, the validity of the LCA cannot be evaluated and the outcomes can be misinterpreted.
5. Practitioners should appropriately qualify the results of an LCA for a remanufactured product, especially in those report sections that are frequently read, such as the abstract and the conclusions. The recommendation by Plevin et al. (2014) to refrain from claims such as "using product X results in a Y% reduction in GHG emissions compared to product Z" (p. 79) is relevant here. Rather, practitioners should formulate a more precise claim, along with a disclaimer, such as "We estimate that the LCA rating of remanufactured product X is Y% lower than that of a newly manufactured equivalent, although this does not imply that producing/using more of remanufactured product X results in a Y% reduction in impacts. This depends, among other things, on how many used products are remanufactured and how often" (based on Plevin et al., 2014, p. 79).

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Appendix A. Literature review details and analysis (part 1 – source material)

Author(s)	Journal or conference proceedings	Goal of study	Summary of LCA goal(s) (author's interpretation)	FU description	Reported LCA result(s)
Amaya et al. (2010)	17th CIRP International Conference on Life Cycle Engineering	"In this project, a Life Cycle Assessment [3], life cycle bricks [4], and a parametric model of the products are used to evaluate and compare the environmental benefits provided by the remanufacturing. The method can support the decision to change the business model and to reorient the activity from cradle-to-grave to cradle-to-cradle while testing different final disposition scenarios." (p. 1)	1) To compare the environmental benefits provided by remanufacturing 2) To support decision making in the firm (change business model/reorient to cradle-to-cradle)	n.a.	"The scenario with a second use phase and 25% of the injector recovered has an environmental gain of 8.64% compared to the cradle to grave scenario. That environmental benefit increases according to the improvement of the rate of remanufactured products. With three product use phase and 100% of injectors recovered, the scenario is 46.10% less impacting than the cradle to grave injector life cycle." (p. 6)
Biswas et al. (2013)	Journal of Remanufacturing	"However, so far, the literature reviewed did not estimate the environmental advantages of remanufacturing over repairing in Australia and elsewhere. The environmental performance of repair and remanufacturing was thus carried out by a detailed LCA" (p. 2)	1) To compare environmental performance of repairing an air compressor and remanufacturing an air compressor	"The compressor used in this case study is a 20HPBitzer compressor (Bitzer Kühlmaschinenbau GmbH, Sindelfingen, Germany) for refrigeration and/or air conditioning. […] this analysis is only based on the GHG emissions associated with repairing, remanufacturing and producing new refrigeration and air-conditioning compressors." (p. 2)	"Since a remanufactured compressor offers a longer life than a repaired compressor, the replacement of the latter with the former can avoid 33–66% of the greenhouse gas emissions associated with a new compressor production with a lifetime of 15–25 years." (p. 1)
Fatimah et al. (2013)	Journal of Remanufacturing	"[…] assessing and improving the SMEs' remanufacturing auto parts in Indonesia and seeks to come up with the best solutions and strategies […]" (p. 3)	1) To assess the remanufacturing of auto parts in SMEs in Indonesia 2) To come up with best solutions and strategies	n.a.	"The use of recycled components in the remanufactured alternator could help attain the threshold values for sustainable manufacturing, including […] GHG emission (2.48 kg CO_{2eq}) and solid waste (0.10 kg) […]" (p. 10).
Goldey et al. (2010)	Proceedings of the 2010 IEEE International Symposium on Sustainable Systems and Technology	"[…] LCAs be done on both the new and remanufactured versions of the product so the full environmental benefits from remanufacturing are captured." (p. 2) "[…] provides an in-depth quantitative assessment of the eco-impact benefits associated with remanufacturing telecommunications equipment." (p. 2)	1) To assess the eco-impact benefits associated with remanufacturing telecommunications equipment	"the telecommunication services provided by the wireline and wireless products over the span of their typical lifetime of ten years […] the analysis contains two successive life cycles of a new product (i.e., two new products placed on the market) versus the life cycle of a recovered product that has been remanufactured (i.e., one new product replaced by a remanufactured product)" (p. 2)	"For the remanufacturing cases studied, the Global Warming Potential (GWP) in terms of kilograms of carbon dioxide equivalents calculated for the remanufactured wireline and wireless products showed a reduction of 44% and 30% respectively, as compared to manufacturing a new product." (p. 6)
Kerr and Ryan (2001)	Journal of Cleaner Production	"To date, surprisingly few other studies have attempted to quantify the environmental benefits of remanufacturing, and none of these takes into account the entire product life cycle. This study was an	1) To assess the contribution of remanufacturing to reducing total resource consumption and waste generation	"It was assumed for each life cycle that 12 million copies are produced over a maximum period of ten years." (p. 78)	"The study found that remanufacturing can reduce resource consumption and waste generation over the life cycle of a photocopier by up to a factor of 3, with

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Author(s)	Journal or conference proceedings	Goal of study	Summary of LCA goal(s) (author's interpretation)	FU description	Reported LCA result(s)
		attempt to begin filling this gap in knowledge by quantifying the overall life cycle environmental benefits of remanufacturing, based on a study of the Xerox Corporation's remanufacturing system […] The purpose of this study was to analyze a well-established remanufacturing system by following the life cycle of a product, to generate data able to provide a more rigorous assessment of the contribution of remanufacturing to reducing total resource consumption and waste generation. […] The study was based on a comparison of the life cycles of remanufactured and non-remanufactured Xerox photocopiers in Australia." (p. 76–77)			greatest reductions if a product is designed for disassembly and remanufacturing." (p. 75)
Lindahl et al. (2006)	Proceedings of CIRP Life Cycle Engineering	"This paper aims at identifying general environmental pros and cons with remanufacturing. The aim is to do so by using different existing, practical examples of remanufacturing industries." (p. 447)	1) To identify general pros and cons with remanufacturing	"The functional unit used for the two appliances in both scenarios were one refrigerator (Electrolux ERB3105) and one washing machine (AEG Lavamat 72330W)" (p. 148)	"As shown in the tables, the environmental reduction is in general considerable, and the remanufacturing process part of the environmental impact is relatively low in relation to the manufacturing part. […] if the products are redesigned to remanufacturing, their environmental impact for remanufacturing has the potential to decrease, implying an even higher environmental reduction." (p. 451)
Lindahl et al. (2014)	Journal of Cleaner Production	"The paper quantifies and discusses environmental and economic effects of concrete IPSOs [Integrated Product Service Offering] in practice in comparison with the product-sales type business […] it also aims to show what engineering activities contribute to those effects, as well as their enablers" (p. 288)	1) To quantify environmental effects of an integrated product service offering 2) To show what engineering activities contribute to those effects	"the functional unit was compaction of soil corresponding to a distance of 1mat a width of 0.55 m; in other words, the functional unit is 0.55 m^2 of compacted soil" (p. 293)	"Generally, the results show clearly that the longer the leasability the soil compactor is assumed to have, the less environmental impact per square meter of packed soil. […] The LCA result shows that zinc used for galvanization can provide a greater environmental impact. It should be noted that data for both painting and repainting show that the environmental impact is limited, e.g. no transport to and from repainting are included in the results." (p. 294)
Liu et al. (2014)	Journal of Industrial Ecology	"An LCA can help decision makers select the product or process that results in the least impact to the environment. In this article, a comparative LCA is conducted for an originally manufactured diesel engine and compared with its remanufactured counterpart, aiming to identify the negative impact on the environment during the whole life cycle and	1) To analyze the environmental potential of remanufacturing diesel engines	"300,000 km (km) driven using a WD615–87 diesel engine" (p. 569)	"The results show that diesel engine remanufacturing could reduce 66% of energy consumption, compared to original manufacturing. The greatest benefit related to environmental impact is with regard to ODP, which is reduced by 97%, followed by EP, GWP, POCP, AP, and ADP, which can be reduced

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Author(s)	Journal or conference proceedings	Goal of study	Summary of LCA goal(s) (author's interpretation)	FU description	Reported LCA result(s)
		analyze the potential that remanufacturing possesses in terms of energy savings and environmental protections” (p. 569)			by 79%, 67%, 32%, 32%, and 25%, respectively.” (p. 1)
Schau et al. (2012)	Journal of Remanufacturing	“This paper presents the results from a multidisciplinary research project applying LCSA on different scenarios for remanufactured alternators – three different countries and three different alternator designs are investigated – and thereby lead contribution to the development of the LCSA methodology […] the main focus in this paper is on the remanufacturing process. Thereby, the measurements to improve the sustainability of the remanufacturing have been identified. Where data permits, the comparison between the new alternators and the remanufactured ones is performed” (p. 2–3)	1) To develop a LCSA methodology 2) To compare between new alternators and three design alternatives for remanufactured alternators in three different countries	“to facilitate the comparison of the new alternators to the remanufactured alternator, the FU of [generating the necessary electricity for the automobile during] 200,000 km is used also on the remanufactured alternator” (p. 4)	“The case study results show that remanufacturing potentially causes about 12% of the emissions and costs compared to producing new parts.” (p. 1)
Smith and Keoleian (2004)	Journal of Industrial Ecology	“The current study provides a more comprehensive assessment of the potential environmental and economic benefits of engine remanufacturing […] The manufacture of a new engine is used as the baseline for comparison.” (p. 195)	1) To assess the potential environmental benefits of engine remanufacturing with the manufacturing of a new engine as a baseline	“The functional unit for this study was defined as the complete service lifetime distance of 120,000 mi (193,000 km) for a 1995 generic vehicle”	“The life-cycle model showed that the remanufactured engine could be produced with 68–83% less energy and 73–87% fewer carbon dioxide emissions. The life-cycle model showed significant savings for other air emissions as well, with 48–88% carbon monoxide (CO) reductions, 72–85% nitrogen oxide (NOx) reductions, 71–84% sulfur oxide (SOx) reductions, and 50–61% nonmethane hydrocarbon reductions. Raw material consumption was reduced by 26–90%, and solid waste generation was reduced by 65–88%.” (p. 193)
Sutherland et al. (2008)	CIRP Annals – Manufacturing Technology	“While many industry-wide studies of remanufacturing have been undertaken, little work has focused on the difference between manufacturing and remanufacturing in terms of CO_2 emissions or energy consumption attributed to specific products. In this paper, the energy benefits of remanufacturing are presented for the major components of a large diesel engine. The broader implications of large-scale remanufacturing are then examined across multiple product use cycles.” (p. 6)	1) To present the energy benefits of remanufacturing the major components of a large diesel engine 2) To examine the broader implications for remanufacturing across multiple product use cycles to support product and recovery system designers	Not provided	“Model results showed that increases in core remanufacturability efficiency could significantly reduce energy consumption (and GHG emissions) per part over multiple use cycles.” (p. 8)
Warsen et al. (2011)	Proceedings of the 18th CIRP International Conference on Life Cycle Engineering	“The aim of this LCA-study is to analyze and compare the environmental impacts of a newly manufactured transmission model with a genuine remanufactured	1) To compare impacts of a remanufactured transmission model with its newly manufactured equivalent	“The manufacture of a type a type MQ250 transmission” (p. 68)	“Energy consumption is reduced by 33% for the remanufactured transmission compared with a newly manufactured transmission.” (p. 67)

(*continued on next page*)

(*continued*)

Author(s)	Journal or conference proceedings	Goal of study	Summary of LCA goal(s) (author's interpretation)	FU description	Reported LCA result(s)
		transmission of identical design." (p. 67)			
Zanghelini et al. (2014)	Journal of Cleaner Production	"[…] unlike manufacturing, the environmental performance of EoL strategies (mainly remanufacturing) has not been well quantified […] a need for more research to quantify the environmental gains of possible EoL scenarios with a life cycle point of view […] this paper aimed to assess the environmental impacts of an air compressor in Brazil with focus on the comparison of three waste management alternatives from cradle to the grave" (p. 165)	1) To compare environmental gains of three EoL scenarios (i.e., landfilling, recycling, remanufacturing) for an air compressor	"the functional unit (FU) is 3,500,400.00 m^3 of air compressed at 7.5 bar of pressure. Although the use phase was estimated to be 10 years with 11 h/day of operation, the FU accounted for the total amount of compressed air generated over 30 years of use of this compressor. This was necessary because it was estimated that the remanufacturing adds 5 years to the lifetime of a remanufactured air compressor. […] Thus, it was necessary equalize the use phase to guarantee a fair comparison between the scenarios by analyzing three life cycles of the equipment for landfilling and recycling and only two life cycles with a lifetime of 15 years each for remanufacturing" (p. 167)	"Remanufacturing was able to reduce the environmental impact by more than 40% compared to Landfilling through a reduced consumption of raw materials, manufacturing processes and environmental gains of avoided products" (p. 164)

Appendix B. Literature review details and analysis (part 2 — content analysis results)

Reviewed articles	Goal and scope of study		Functional unit (FU)			Reference flow (RF) model			Excluded life cycle stage(s)	Type of perspective
	Type of motivation	Type of product(s) in LCA	Type of FU	Magnitude of function in FU	Duration/life span in FU	Used product in reference flow model?	#Remanufacturing cycles	Analysis of multiple cycles		
Amaya et al. (2010)	Method	Engine injector parts	Unknown	Unknown	Unknown	Unknown	1–2	Yes	Use stage	Unknown
Biswas et al. (2013)	Universal	Air compressor	Product-based FU	No	No	No	1	No	Use stage	Supporter
Fatimah et al. (2013)	Universal	Engine alternators	Unknown	Unknown	Unknown	Unknown	1	No	Unknown	Unknown
Goldey et al. (2010)	Specific	Wireless switching product Wireless base station	Product-based FU	No	Yes (20 years)	Yes	1	No	Use stage	Neutral
Kerr and Ryan (2001)	Universal	Two photocopier models	Function-based FU	Yes	Yes (10 years)	No	1	No	Use stage	Supporter
Lindahl et al. (2006)	Universal	Toner cartridge, Forklift truck, Car brake calipers	Unknown	Unknown	Unknown	No	2, 0.5, 1	No	Use stage	Unknown
Lindahl et al. (2014)[b]	Specific	Soil compactor	Function-based FU	Yes	Yes (5–8 years)	Unclear	1	No	Unknown	Unknown
Liu et al. (2014)	Specific	Diesel engine	Product-based FU	Yes	Yes[a] (300,000 km)	No	3–5	No	Use stage EoL	Supporter
Schau et al. (2012)	Method	Engine alternators	Product-based FU	Yes	Yes[a] (200,000 km)	Yes	1	No	None	Supporter
Smith and Keoleian (2004)	Specific	Midsized automotive gasoline engine	Product-based	Yes	Yes[a] (193,000 km)	No	2–4	No	Use stage	Supporter
Sutherland et al. (2008)	Specific	Large diesel engine	Unknown	Unknown	Unknown	Yes	1–10	Yes	None	Unknown
Warsen et al. (2011)	Specific	Engine transmission	Product-based	No	No	No	1	No	Use stage EoL	Supporter
Zanghelini et al. (2014)	Universal	Air compressor	Function-based	Yes	Yes (30 years)	Yes	1	No	Use stage	Neutral

[a] Duration/life span is set equal to the magnitude of the service in the FU.

[b] The soil compacter LCA is reviewed only (i.e., "case study III") in Lindahl et al. (2014).

Appendix C. Two additional perspectives: the ‘full activity’ and ‘factory’ perspectives

Two other perspectives that can be adopted in carrying out an LCA for remanufacturing are presented in this Appendix. These perspectives are referred to as the ‘full activity’ perspective and the ‘factory’ perspective. Both perspectives have not been found in any of the papers reviewed and are chosen arbitrarily. Other perspectives are possible too. The perspectives will be introduced first, and illustrated with the Neopost Folder Inserter case study. In addition, the results of these two additional perspectives will be compared with the results ‘supporter’ and ‘neutral’ perspectives as discussed in the paper (see Fig. 5 and Table 6).

The ‘full activity’ perspective assesses the environmental benefits of using remanufactured equipment in the activity, or activities, for which the product is used. In Table C7, FU-3 reviews the environmental benefits of the remanufactured folder inserter in the light of the process in which the folder inserter is used in companies, i.e., for sending out mail. The function of folding and inserting mail items is but one of many processes in sending out mail (e.g., mail design, paper production, printing, and distribution). The RFs cover all the materials and processes required for preparing and sending out mail, with only one difference: using one NEW DS-63 or one remanufactured FPNM DS-63.

Table C7
Goals, FU and RFs for the ‘full activity’ and ‘factory’ perspectives.

Type of perspective	Goal	Definition of FU	RFs
FU-3 ‘Full Activity’ perspective	To analyze the environmental benefits of using a remanufactured folder inserter compared to newly manufactured equipment. The results can be used to decide whether or not to buy or lease a remanufactured product or a newly manufactured product.	Send out 15,000 mail pieces (marketing material) per month for five years	• All materials and activities for preparing and sending mailings including one NEW DS-63 • All materials and activities for preparing and sending mailings including one FPNM DS-63
FU-4 ‘Factory’ perspective	To analyze the environmental benefits of remanufacturing folder inserters in a hybrid new manufacture–remanufacturing system compared to only producing new equipment. The results will be used to inform stakeholders about the current environmental benefits of the firm's remanufacturing activities compared with conventional manufacturing activities.	Produce DS-63 equipment to fold and insert 30 million mail pieces per month for five years	• Materials and activities for 400 NEW DS-63 + 900 FPNM DS-63 • Materials and activities for 1300 NEW DS-63 machines

Table C8
Life cycle inventory (LCI) for FU-4.

Functional unit number	Product system name and reference flows	Raw materials	Manufacturing	Distribution	Use	End-of-life & reverse logistics
FU-3	See Table C10					
FU-4	1300 NEW DS-63s 400 NEW DS-63 and 900 FPNM DS-63	1300 NEW DS-63 400 NEW DS-63 + 900 FPNM DS-63	1300 NEW DS-63 400 NEW DS-63 + 900 FPNM DS-63	1300 NEW DS-63 400 NEW DS-63 + 900 FPNM DS-63	1300 NEW DS-63 400 NEW DS-63 + 900 FPNM DS-63	1300 NEW DS-63 400 NEW DS-63 + 900 FPNM DS-63

The ‘factory’ perspective provides an assessment based on a remanufacturing company's total manufacturing activities. The ‘factory’ perspective provides information for a remanufacturing company concerning the environmental performance of a hybrid manufacturing–remanufacturing production system. In Table C7, FU-4 is based on the ‘factory’ perspective. The demand volume for Neopost's DS-63 folder inserters is approximately 1300 units per year. Given the capacity of each machine, this amounts to a total capacity demand for folding and inserting of 30 million mail pieces per month. Based on information provided by Neopost, 900 DS-63 models are remanufactured (into FPNM DS-63 models) on average each year (70% of all DS-63 folder inserters produced annually) and the remaining 400 machines are newly manufactured. The alternative production scenario, which does not include remanufacturing, would fulfill this FU by making 1300 new DS-63 folder inserters.

FU-3 was not part of the original LCA, and therefore LCI data and results are not available. A report by Pitney Bowes Inc (2008)[1] has therefore been used to estimate the impacts of other activities such as paper production and mail distribution (see Table C10). Also, omitting life cycle stages is not permitted in FU-3 because it concerns the *full* activity perspective. The LCI for FU-4 in Table C8 is a variation of FU-1 (see Table 5).

Fig. C6 depicts the results of the ‘full activity’ and ‘factory’ perspectives next to the results of the ‘supporter’ and ‘neutral’ perspectives as discussed in the paper. The ‘full activity’ perspective (FU-3) produces the lowest relative environmental benefit of just 0.78% (expressed in GWP) through using a remanufactured folder inserter rather than a new one. In contrast, at the other extreme, adopting the ‘supporter’ perspective (FU-1) and excluding the use and distribution life cycle stages produces an environmental benefit of 47.21%. Taking the ‘neutral’ perspective (FU-2), the relative advantage falls significantly to less than 23.6%. The ‘factory’ perspective (FU-4) would suggest to the remanufacturer, i.e., Neopost, that their hybrid new manufacturing/remanufacturing DS-63 production system reduced the GWP by 32.68% compared to the previous situation without remanufacturing and excluding the distribution and use stages. One should also note that the ‘factory’ perspective illustrated here adopts a short-term perspective and that the relative GWP saving will vary from year to year.

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[1] This report can be downloaded from: http://www.pitneybowes.ca/docs/International/canada/en/pdf/Environmental Impact of Mail.pdf (last date accessed: May 7, 2015).

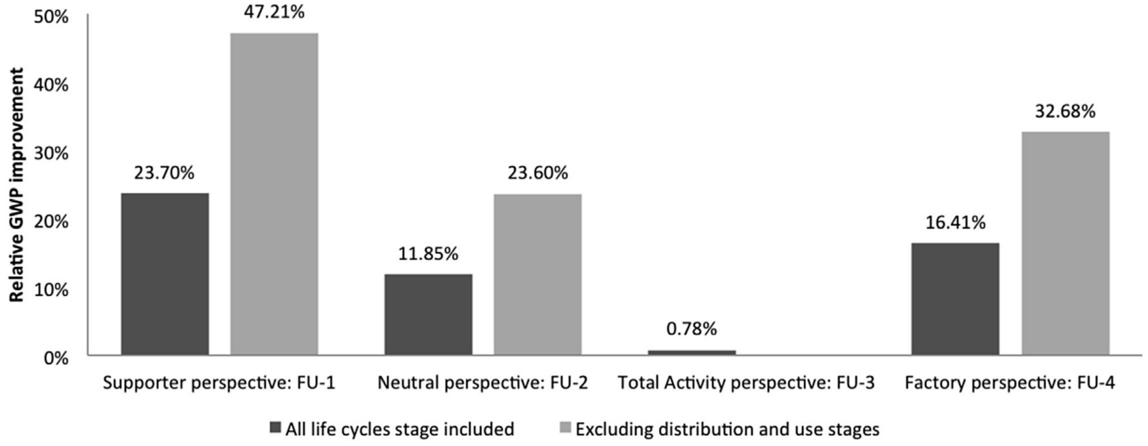

Fig. C6. Comparison of relative environmental benefits for the four different perspectives and functional units. Note that omitting life cycle stages is not permitted in FU-3, and therefore this result is not listed.

Table C9
Results of LCIA expressed in terms of Global Warming Potential (in kg CO_{2eq}) for the ‘full activity’ and ‘factory’ perspectives and functional units.

	Alternative	Raw materials & manufacturing	Distribution	Use	End of life & reverse logistics	Total	Total without distribution and use stages	Absolute and relative difference to NEW	Absolute and relative difference to NEW (without distribution and use stages)
FU-3	Sending mails with NEW DS-63	–	–	–	–	**21,773**[a]	–	169 **0.78% ⇩**	–[b]
	Sending mails with FPNM DS-63	–	–	–	–	**21,604**[a]	–		
FU-4	1.300 NEW DS-63	458,900	106,600	354,900	6500	**926,900**	**465,400**	152,100	152,100
	400 NEW DS-63 + 900 FPNM DS-63	305,000	106,600	354,900	8300	**774,800**	**313,300**	**16.41% ⇩**	**32.68% ⇩**

Notes. ⇩ denotes a reduction in GWP impact due to remanufacturing.
[a] Estimate of total GWP impact for FU-1b. See Table C10 for a breakdown, assumptions, and sources.
[b] Omitting life cycle stages is not permitted in FU-3.

Table C10
Break-down of total estimated impacts for FU-3.

Activities	Value	Unit	Source
Total upstream activities (design, Production of materials and Production of the mail piece)	1.10	gram CO_2 per sheet	“According to a review of more than a dozen studies, the indicative range of CO_2 emissions associated with the upstream mail piece creation process (Stages 1–3, Design, Production of materials and Production of the mail piece) is about 0.9–1.3 g of CO_2 per gram of paper.” (Pitney Bowes Inc, 2008, p. 16)
Average sheets per mailing (including envelope)	5.00	sheets	Assumption made by author
Total impact upstream activities per mailing	5.30		
Impact of distribution by post	17.90	gram CO_2 per mailing	“[…] the indicative range of CO_2 emissions per letter handled within the Posts appears to be 10–30 g. The median of the 14 sources listed in Table 5 is 17.9 g per letter.” (Pitney Bowes Inc, 2008, p. 12)
Inserting and folding with NEW DS-63	0.79	gram CO_2 eqv per insert	Based on the DS-63 LCA
Inserting and folding with FPNM DS-63	0.60	gram COeqv per insert	Based on the DS-63 LCA
Total impact of sending one mailing with NEW DS-63	24.19	gram CO_2 eqv	
Total impact of sending one mailing with FPNM DS-63	24.00	gram CO_2 eqv	

Summary	gram CO_2 eqv	kilogram CO_2 eqv
Total impact of sending 15,000 mailings per month with NEW DS-63 for a period of 5 years	21,773,000	21,773
Total impact of sending 15,000 mailings per month with FPNM DS-63 for a period of 5 years	21,604,000	21,604
Absolute difference: estimated benefit of the FPNM DS-63	**169,000**	**169**
Relative difference: estimated benefit of the FPNM DS-63	**0.78%**	**0.78%**

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