Environmental Issues within the Remanufacturing Industry

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Abstract

Researchers often regard remanufacturing as an environmentally beneficial end-of-life option. There have been, however, few environmental measurements performed in the area. The aim of this paper is to identify general environmental pros and cons with remanufacturing. This is done through the analysis of practical examples in remanufacturing industries. Life Cycle Assessment methodology has been used for the environmental validations.

The first conclusion, based on the industrial cases and the literature review, is that remanufacturing is preferable from a material resource perspective when compared with manufacturing of new products. The second conclusion is that remanufacturing is preferable from a more overarching perspective for some of the investigated cases, but it is not possible to draw any general conclusions since the companies studied are few and benefits from remanufacturing are highly context-related.

Keywords

Remanufacturing, Life Cycle Assessment, Design for Environment

1 INTRODUCTION

The remanufacturing industry got a boost during the Second World War when many manufacturing facilities changed from ordinary production to military production, and therefore the products in use were to a large extent remanufactured in order to keep society running. The concept of remanufacturing has spread during the latest decades to sectors such as those dealing with automotive products and components, electrical apparatus, toner cartridges, home appliances, machinery, cellular phones etc. see e.g. [1]. Furthermore, the concept of remanufacturing is also spreading throughout the world; in Sweden, for example, more and more remanufacturers have recently appeared [2].

Many definitions for remanufacturing can be found, see e.g. Lindahl *et al.* [3] for a mapping, but most are variations of the same basic idea of product rebuilding. The used/worn-out/broken products that enter the remanufacturing process are often called 'cores'. This term will also be used in this paper. In studying the various definitions, the authors identified a combination of the definitions useful for the meaning of remanufacturing in this paper. In this paper:

'Remanufacturing is an industrial process whereby products referred as cores are restored to useful life. During this process the core pass through a number of remanufacturing steps, e.g. inspection, disassembly, part replacement/refurbishment, cleaning, reassembly, and testing to ensure it meets the desired product standards' [1].

Not all firms engaged in remanufacturing call themselves remanufacturers, however; many in the automobile component remanufacturing sector prefer to use the term 'rebuilding'. Similarly, tire remanufacturers call themselves 'retreaders', while laser toner cartridge remanufacturers consider themselves 'rechargers' [4]. If the rebuilding of the product is not extensive, i.e., if few parts are to be replaced, either of the terms reconditioning or refurbishing is more suitable. Reconditioning/refurbishing is also used when the product is only remanufactured to its original specifications [5]. Remanufacturing, in any event, is becoming the generic term for the process of restoring discarded products to useful life [4].

The incentives for starting up a remanufacturing business are numerous and dependent on, for example, where the company is situated and which products are to be remanufactured. The authors have identified the following three incentives to start remanufacturing [1]:

- market demand
- legislation, and
- environmental issues.

At manufacturing companies having their own remanufacturing facilities, the remanufacturing volumes of today are normally much lower than the manufacturing volumes[1]. Some manufacturers do not want to remanufacture their products, however, since they claim that they will compete in the same market as the ones that are newly manufactured [1]. Although this statement is true to a degree, other researchers have found that original equipment remanufactures have much to learn as far as running their own remanufacturing businesses (see e.g. Jacobsson [6]). Other researchers, such as Seitz and Peattie [7], further confirm several benefits for manufacturers who begin to remanufacture their products, such as a secure supply of spare and replacement parts. Furthermore, for low-volume parts or phased-out products, remanufacturing could speed up the supply of replacement products for customers [7]. In some cases, the product also can be monitored during its use, and information gathered could be useful in the remanufacturing process.

2 AIM

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.

3 METHODOLOGY

The first step was a literature review with a focus on environmental aspects of remanufacturing. As the second step, a study was conducted at Electrolux dealing with the recycling and remanufacturing of two household appliances. In the third and last step, three products from three companies were studied in order to get a rough

[1] Two exceptions to this are e.g. the remanufacturing of forklift trucks and single-use cameras as described by Sundin [1].

overview of the environmental pros and cons with remanufacturing.

3.1 Methods for the analysis of household appliances

The first analysis was addressed through a literature review and by performing an environmental assessment of the refurbishment of household appliances at Electrolux AB in Motala, Sweden. Furthermore, a comparison was made between two scenarios concerning the end-of-life scenario for household appliances at Electrolux. In order to make these scenarios as comparable as possible, similar system boundaries for the different analyses were used. The scenarios begin when and where a household appliance has broken down in Sweden. Repairmen then have three attempts to repair the appliances at the customer's location. After these three attempts, the appliances are transported to the local service centre, where the two scenarios of refurbishment and recycling begin. Most of the data for the analyses was gathered through literature, the Internet and communication with employees at Electrolux. Other companies were also contacted in order to acquire data for transportation and recycling. The scenarios are described in detail in Sundin and Tyskeng [8].

The environmental effects for the different scenarios were compared using life cycle analysis methodology. The tool for conducting the inventory portion of the assessment was a software application called LCAiT[2]. Previously conducted LCAs and Environmental Product Declarations (EPDs) by Electrolux were used to gather the right information about the products. The functional unit used for the two appliances in both scenarios were one refrigerator (Electrolux ERB3105) and one washing machine (AEG Lavamat 72330W), respectively, as seen in Figure 1.

Figure 1. The products analysed at Electrolux AB.

3.2 Methods for the third analysis

The major base for data used in this step has been the Swedish Governmental Agency for Innovation Systems (VINNOVA) supported project titled "Sustainable Systems and Products for Remanufacturing and Refurbishment (REKO)". The overall aim of this project is to, in cooperation with several companies, develop a foundation for the improvement of environmental, work relation and economic issues in the area of reuse and reconditioning/remanufacturing.

Most of the data for the analyses were gathered through study visits and interviews with employees, literature and the Internet. The environmental effects for the different scenarios were compared using LCA methodology. The tool for conducting the inventory portion of the assessment consisted of author-developed Excel-based LCA calculation sheets. Data used are from e.g. Boustead [9], NTM [10] and Sunér [11]. The functional unit used for each product analysed was "one product with a normal lifetime". This is in line with the Electrolux analysis. The scenarios that were compared was remanufacturing with recycling as the final step and the production of new products with recycling. Several different validation methods were selected to be able to compare if the validation method had a major influence on the general outcome. For more information about the validation methods see [12-14].

4 LITERATURE REVIEW

Upon reviewing literature concerning the environmental impacts of remanufacturing, it is evident many researchers consider the concept of remanufacturing as one of the most preferable options to choose from when determining end-of-life scenarios (see e.g. Graedel and Allenby [15], Ryding *et al.* [16], Jacobsson [6], and Steinhilper [17]). The energy required to remanufacture a product is significantly less than that used in recycling - provided the product fits the necessary production characteristics of remanufacturing [4]. Much of this research refers to the fact that with remanufacturing, the efforts put into manufacturing for shaping the product and its parts is salvaged in comparison to for example material recycling.

In the literature, there are few thorough research studies involving environmental remanufacturing analyses to be found. One example of an analysis conducted by Kerr [18] is that of the remanufacturing of Xerox copy machines. Kerr performed a comparison between the remanufacturing of a traditionally-designed copy machine and a copy machine that was designed to facilitate remanufacture. For the Xerox model DC 265, which has been designed for remanufacturing, the savings of energy equal a factor of 3.1 and those of materials and landfill waste a factor of 1.9.

Another study analysing environmental and economic perspectives on the remanufacturing of gasoline engines was conducted by Smith and Keoleian [19]. They developed a LCA model in order to in the United States through the remanufacturing of a mid-sized automotive gasoline engine. Furthermore, a comparison was made to an original equipment manufacturer manufacturing a new engine. A typical full-service machine shop, which is representative of 55 percent of the engine remanufactures in the United States, was inventoried, and three scenarios for part replacement were analysed. The life-cycle model showed that the remanufactured engine could be produced with 68 to 83 percent less energy and 73 to 87 percent fewer carbon dioxide (CO_2) emissions. Furthermore, the model showed significant savings for other air emissions as well, with 48 to 88 percent carbon monoxide (CO) reductions, 72 to 85 percent nitrogen oxide (NO_X) reductions, 71 to 84 percent sulphur oxide (SO_X) reduction, and 50 to 61 percent non-methane hydrocarbon reductions. In addition, raw material consumption was reduced by 26 to 90 percent, while solid waste generation was reduced by 65 to 88 percent. The comparison of environmental burdens was accompanied by an economic survey of suppliers of new and remanufactured automotive engines showing a price difference for the consumer between 30 to 53 percent for the remanufactured engine, with the greatest savings

[2] The software was developed by CIT-Ekologik at Chalmers Industriteknik, a research organisation at Chalmers University of Technology, Sweden.

realized when the remanufactured engine is purchased directly from the remanufacturer. [19]

Although these figures show economic and environmental benefits for remanufacturing in comparison to new manufacturing, the study also showed that a small change in fuel efficiency could reduce the environmental benefits of remanufacturing.

This presented literature review presented above is further discussed in Sundin [1].

5 REFURBISHING VERSUS RECYCLING AT ELECTROLUX AB

The analysis consisted primarily of an environmental comparison of end-of-life scenarios for two household appliances. Electrolux has learned from experience that household appliances often break down during use or are damaged during transportation. These broken/damaged appliances arrive at various service centres all over Sweden. In the first scenario, the appliances are material recycled close to the service centres. In the second (existing) scenario, the appliances are transported by heavy trucks and remanufactured in a facility in Motala, Sweden. The methodologies used were LCA modelling as earlier mentioned. The two scenarios of remanufacturing and material recycling are also compared with the manufacturing of new appliances. In the refurbishing scenario, 16.7 percent of the refurbished products are material recycled and are accounted for.

For the washing machine, a large number of transports in the remanufacturing scenario resulted in higher emissions of greenhouse gases. These emissions are 12 times higher than in the recycling scenario. On the other hand, the greenhouse gas emissions are more than 60 times higher for new production in comparison to remanufacturing. For the refrigerator, the Isobutane R600a and cyclopentane used as refrigerant and cooling agents are taken care of in the refurbishment scenario, which makes the recycling scenario less desirable when considering greenhouse gas emissions.

There were differences in the life cycle inventory results between a refrigerator and a washing machine; these can be explained mainly by their weight difference and thus increased emissions in the transport of a refrigerator. The acidifying effect of remanufacturing is smaller than that of recycling in the case of both the refrigerator and the washing machine. The usage of heavy machinery at the recycling facilities also causes emissions. The difference between the emissions of the remanufacturing scenario is again caused by the different weights of the machines. The release of ground level ozone gases is fairly marginal in both scenarios. This effect category has little significance in this research. Nitrogen and phosphorous compounds are the main causes of eutrophication. The usage of laundry detergents and washing agents in the test and clean-up phases of washing machines explains the higher amount of eutrophication compounds released when being remanufactured.

When reading the LCI results, it is most interesting to compare remanufacturing with new production since the end product of those scenarios is more similar. An interesting comparison would be to have the recycled material become a part of a newly manufactured product; in that case, the remanufacturing and recycling scenario would be more comparable. If this were the case, more actions, like transports from the local recycler to the manufacturing facility, would be added. In the previously described analyses by Kerr [18] and Smith and Keoleian [19], the comparisons were between remanufactured and new manufactured products. This shows that the setting of the system boundary is crucial in determining which results will be achieved.

All in all and from an environmental point-of-view, remanufacturing seems in this analysis to be a sound way to achieve functional products. The remanufacturing process results in a functional product, while recycling only provides material. A negative aspect compared to recycling is the need for longer transports, as Electrolux has only one refurbishment facility in Sweden. By using sophisticated logistics in cooperation with transport companies, the number of transports needed has been minimized. Energy consumption at the facility is fairly small, as most of the work is done manually.

In comparison with the production of a completely new product, the emissions and energy needs resulting from refurbishment are very small. The amount of energy needed to produce a new refrigerator is 50 times greater than the energy needed for refurbishment. The production of a new washing machine requires 30 times more energy than the refurbishment of such a product. Similarly, the need for material resources is much greater when producing completely new products. The usage of materials is becoming an important issue, as non-renewable resources are diminishing.

These results are in line with an analysis made by Electrolux that also shows that the emissions caused when refurbishing refrigerators are smaller than those generated in the recycling scenario. Furthermore, the Electrolux study had smaller system boundaries, which made this analysis more thorough. According to Electrolux, the energy savings when remanufacturing its appliances in Motala versus manufacturing new products was equal to that required to heat 250 houses for a year[3].

Furthermore, it was shown that the refurbishment of household appliances in the Motala facility was profitable; this was also shown in the study conducted by Smith and Keoleian [19]. One must also consider the value of reselling the product, environmental image, and the costs and loss of yield for new manufacturing (applicable if they are in the same market). These results are also discussed in e.g. Sundin *et al.* [20], Sundin and Tyskeng [8] and Sundin and Bras [21].

6 THE REKO INDUSTRIAL CASE STUDIES

The different industrial cases are briefly described below, with the LCA result presented in the final section.

6.1 Toner cartridge case

The toner business is regulated under take-back laws, and thus its products cannot be treated as ordinary office supplies since they have been previously used. This creates a recycling problem for the customer. The company investigated recognizes the embedded value in the discarded product that can be realized through remanufacturing. By managing the relationship with the customer, a win-win situation is created. A recycling service is given to the customer free of charge, and results in the access to used toner cartridges. The relationship is established by providing a take-back system that is realized with a return box that is (when full) sent to the company free of charge. The take-back system also motivates customers to remain customers and provides a sales opportunity, since a customer is more likely to purchase remanufactured cartridges when they are supplying the used ones through the take-back system. Within the group, there are three different

[3] According to unpublished calculations made by Gianluca Brotto, Electrolux AB.

remanufacturing plants located in Europe. To balance the need of cores, they collaborate by supplying the demanded cores on a European level.

The Process – The remanufacturing process is as follows. The toner cartridges are sent randomly to the company in boxes from the customer. Each box can hold multiple cartridges. When the box arrives, it is unpacked and undergoes a combined manual operation where the product is simultaneously identified, inspected and sorted. The cartridges are sorted according to a preset standard based on whether they have been used only one time (virgin) or have been remanufactured before (non-virgin). They are also sorted after the status of the core; an example here would be if the cartridge was damaged in some way.

The sorting is also done because of an over-supply of cores, and the best (i.e. virgin) are designated for remanufacturing, while the remaining cores are placed in reserve. Another reason is for capacity management: when there is a demand peak, it is only the virgin cores that can be used, enabling more rapid remanufacturing and thereby a higher remanufacturing volume. Non-virgin cartridges are used in situations of over-capacity, due to the increased time it takes to remanufacture the cartridges.

After the sorting operation, the cores are stored in inventory while waiting for a remanufacturing order. When the order arrives, the cores are sent to a disassembly operation. From this point, some of the parts are sent to a cleaning operation, while others are sent to machining operations to be reprocessed and, in some cases, cleaned. Some of the parts are also sent to recycling/landfills, and new components are used to replace the discarded. The reason for the discarding is either that the components are broken, or due to a policy at the company to always replace the components.

After all parts have gone through reprocessing operations, they are reassembled with the new components. After reassembly, they are tested and packed before they are placed in the finished goods inventory.

6.2 The warehouse equipment supplier case

The warehouse supplier investigated is one of the world's leading actors in the forklift truck industry. The main objective of the warehouse provider is to develop a service that supports the customers' material handling operation. The warehouse supplier has taken extensive actions towards a change from just producing and selling forklift trucks towards providing warehouse service, i.e. functional sale. The Company's business concept is to *anticipate customer needs and deliver solutions for efficient materials handling*. With *cost-effective products and services*, the company aims to provide its customers with trouble-free material handling operations worldwide.

The Company's remanufacturing creates the opportunity for effective functional sales. By providing the function of a forklift truck instead of the physical product, a service opportunity is created. The customer is given the flexibility to use the function of the forklift when needed, and the price is known in advance (including, for e.g., the service cost). When the demand for the function decreases, the customer has the possibility to stop buying the function and return the forklift truck. The forklift truck is then transported to a remanufacturing facility, were it is remanufactured and shipped to the next customer. By providing regular service and maintenance operations at the customer's location, a relationship is established through the service personnel. At the same time, the service personnel gain detailed information as to whether or not there is a need for a future remanufacturing operation. This information makes the return flow of products easier to control and provides information on the truck status to the remanufacturing process.

In this case, the cores are controlled by a take-back system that is ownership-based. In this case, the forklift trucks are linked to a functional sales contract, which gives the company a high degree of control regarding the closed-loop supply chain.

The Process – When the remanufactured products arrive, they are inspected and sorted into different status levels. When a need arrives, they are sent to a remanufacturing shop for disassembly. The forklift always has a fixed position during the remanufacturing process, and the same is true when components are replaced. Some simpler reprocessing of components is also performed, but the components are for the most part replaced with new ones. After functionality testing, the product is painted and shipped out to customer.

6.3 The car brake callipers case

The company that was investigated for this case remanufactures car components. The main product is brake callipers, but it also remanufactures products such as steering racks, steering pumps, master cylinders, etc. The company uses two different closed-loop supply chain models, one applying to the independent customer, and one for the contracts with the OEMs.

Furthermore, the company uses a take-back system that makes the customer return their cores when buying a remanufactured product. This creates a link between both supply and demand chains, adding value to both the customer and the producer. The remanufactured product is sold to the customer with a price and a deposit fee. The customer is obligated to return their used cores in return for a remanufactured one. If the core is not returned, the deposit is charged to the customer, but if returned, the deposit is refunded. For example, when selling an automotive part to a retailer, the retailer pays a deposit fee for the part. The retailer then sends back the used product acquired from the end customer, and the deposit is refunded.

The Remanufacturing Process – This system creates a theoretical match between the supply of cores and the demand for remanufactured products; this is because of the direct link. Although in practice this is not the case, because of the fact that non-usable cores enter the system, spare cores must be acquired by other means. The Company has two different facilities, one in Poland and one in Sweden. The incoming cores arrive at the plant in Sweden where they are inspected and sorted into a company-specific code system that is car manufacturer-independent. No consideration is taken for the quality level of the core; only those that are clearly non-remanufactureable are sorted out from the system.

After sorting, the products are held in stock awaiting a remanufacturing order. When an order is taken, the products are sent to Poland for disassembly. As in the toner cartridge case, the components are sent to different reprocessing operations: repairing, cleaning, blasting and painting. When the components from a batch are reprocessed, they are sent to Sweden for reassembly with complementary new parts that have been discarded.

6.4 The case results from the simplified LCAs

Since the use phase for the products studied has a limited influence on the result, this phase was excluded. For example, even if the energy use for a forklift truck represents a major part of its total environmental impact, this will have minor influence since the forklift truck will be replaced with an equal forklift truck so the energy consumption will not differ. The data collection for the different cases has been difficult, and the data behind the figures in the tables below are limited and mostly focused on transport and material content. Nevertheless, the result provides a rough image of the relations and benefits with remanufacturing. As shown, several evaluation methods were used in the validation of the environmental impacts. In the result tables below, MP is the abbreviation of "Manufacturing Phase", while RP is short for the "Remanufacturing and Recycling Phase" and TOT denotes the "Total Evaluated Environmental Impact". Reduction describes the difference between manufacturing with remanufacturing and manufacturing without remanufacturing. 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. It is also important to consider that the products in those cases have not been designed for ease of remanufacturing. This implies the likelihood that, if the products are redesigned to remanufacturing, their environmental impact for remanufacturing has the potential to decrease, implying an even higher environmental reduction.

Table 1. The Toner Cartridge Case. The toner cartridges is remanufactured 2 times on average[4].

		EPS	ECO S	ET long S	ET norm S
Remanu-facturing	MP	86%	77%	80%	79%
	RP	14%	23%	20%	21%
	TOT	1,7E+00	7,1E+02	2,3E+02	9,1E+01
Without remanu-factacturing	MP	99%	98%	99%	99%
	RP	1%	2%	1%	1%
	TOT	4,5E+00	1,7E+03	5,7E+02	2,2E+02
Reduction		61%	57%	59%	59%

Table 2. The Warehouse Equipment Supplier Case. The forklift trucks are remanufactured 0.5 times on average[4].

		EPS	ECO S	ET long S	ET norm S
Remanu-facturing	MP	97%	89%	91%	90%
	RP	3%	11%	9%	10%
	TOT	1,2E+04	7,9E+05	2,9E+05	1,0E+05
Without remanu-factacturing	MP	100%	96%	97%	96%
	RP	0%	4%	3%	4%
	TOT	1,7E+04	1,1E+06	4,1E+05	1,4E+05
Reduction		32%	28%	29%	29%

Table 3. The Car Brake Callipers Case. The car brake callipers are remanufactured 1 times on average[4].

		EPS	ECO S	ET long S	ET norm S
Remanu-facturing	MP	90%	60%	66%	63%
	RP	10%	40%	34%	37%
	TOT	2,1E+01	2,3E+03	7,5E+02	2,8E+02
Without remanu-factacturing	MP	99%	86%	90%	89%
	RP	1%	14%	10%	11%
	TOT	3,9E+01	3,2E+03	1,1E+03	3,9E+02
Reduction		45%	28%	32%	30%

7 DISCUSSION

Environmental researchers that discuss end-of-life scenarios for products often put remanufacturing as one of the most preferable alternatives [8, 18, 19], considering use of materials. As shown in this paper, the industrial studies support this. The major reason for this is that with product remanufacturing, the geometrical form of the product is retained and its associated economic value is preserved. If the products also are adapted for remanufacturing, there are more environmental benefits achievable (see e.g. Kerr [18]). The fact is that the warehouse equipment supplier that has control over the new production of forklifts is considering design changes to gain more from the remanufacturing system, see e.g. Sundin *et al.* [22].

However, it is dangerous to draw to general conclusion based on the results from the studies presented in this paper, since there were only 4 companies studied and the case studies in the literature are few. The preferable end-of-life scenario for specific cases is often dependent on the remanufacturing context (e.g. which product type, what technology is available or how the product is used). For example, it is important to note that the figures for the Xerox Australia study (Kerr [18], also described in Sundin *et al.* [20]) represent the savings in resource productivity during the manufacturing and disposal phases. To explain further; as photocopy machines are energy and resource intensive during the user phase, this is where the majority of the environmental burden is generated. Consequently, when aggregating the environmental performance of remanufacturing with those generated during the user phase, the savings, in percentage, of remanufacturing are less than if only the manufacturing phase would be considered. Although this indicates that proportional life cycle savings for remanufacturing may be less for products with high-energy intensity during its user phase, the benefits cannot be neglected. From a resource productivity point-of-view, remanufacturing still produces benefits for different levels of energy intensities during the user phase [1].

These issues were also discussed by Smith and Keoleian [19]. In their study, the significance of functional equivalency between new and remanufactured engines was explored. The analysis of potential differences in fuel efficiency between the two engines demonstrated the criticality of this parameter. A one percent improvement in fuel efficiency for a mid-sized automobile powered by a remanufactured engine could double the savings in life-cycle energy, whereas a decrease in efficiency of one percent would negate the benefits provided by the remanufactured engine through avoided materials production and manufacturing [19]. Hence, the technology of the new product, as compared to the remanufactured product, could have high importance on the environmental impact. Parameters like the fuel efficiency described above can alter the results significantly with only a small efficiency parameter change. In order to avoid these technology conserving aspects of remanufacturing, the products should be easy to upgrade to the latest technology.

Finally, when summing up the different results of the analyses, one can see that the analyses show that remanufacturing is in general preferable to other end-of-life scenarios or new production from a material resource perspective, having in mind that the remanufacturing process results in a functional product. These results are in line with the end-of-life priority lists stated by Graedel and Allenby [23], namely:

1. Reduce materials content
2. Reuse components/refurbish assemblies
3. Remanufacture
4. Recycle materials
5. Incinerate for energy (if safe)
6. Dispose of as waste

[4] MP is the abbreviation of "Manufacturing Phase", while RP is short for the "Remanufacturing and Recycling Phase" and TOT denotes the "Total Evaluated Environmental Impact". Reduction describes the difference between manufacturing with remanufacturing and manufacturing without remanufacturing.

8 CONCLUSIONS

This paper has shown that remanufacturing for the industrial cases analysed is a preferable scenario compared with the replacement of newly-manufactured products. This is valid from material resource perspective for all the cases investigated. Furthermore, in the REKO cases the LCA results show that remanufacturing is also beneficial from an overarching environmental perspective.

However, further research studies are required to form an opinion of if this is a general conclusion or not. This is because the benefits from remanufacturing are highly context-related, and it is not clear that remanufacturing is a preferable option since it may lead to a higher amount of emissions derived from e.g. the number of transports required in order to get the cores to the remanufacturing facilities.

9 ACKNOWLEDGMENTS

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