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Comparison of Manufacturing/Remanufacturing CO₂ emissions balance: application to a mowing machine

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Abstract—Today the extraction of virgin raw materials has become more difficult, expensive, and even polluting, especially in the specific case of metals. For solving these problems, product remanufacturing seems relevant. Indeed, it is considered as one of the most effective circularity strategies, contributing in particular to limit the use of raw materials and the associated nuisances. However, it is necessary to quantify its benefits, especially from an environmental perspective. The objective of this article is to compare the CO₂ emissions of a remanufactured product to those of a traditionally manufactured product. The studied product is a roadside mowing machine, which manufacturing and remanufacturing are made in France. The comparison of the two processes was carried out with OpenLCA software and Ecoinvent databases to estimate the CO₂ footprint in each case. Thus, the reduction of CO₂ emissions induced by remanufacturing has been estimated. As a result, a reduction of approximately 80% was found, which corresponds to the reduction of raw materials, including steel and iron, and the corresponding processed.

Keywords—Remanufacturing, life cycle assessment process, circular economy, CO₂ emission, mowing machine.

I. INTRODUCTION

Industrial activities account for about 20% of the world's greenhouse gas emissions. In addition, the extraction of virgin raw materials has become more difficult, expensive, and even polluting, especially in the case of metals. This poses supply, economic and ecological problems for companies and society [1]. To solve these problems, a new production model able to reduce waste and ensure the existence of raw materials in an economically viable way has been proposed: the circular economy (CE). It represents a new economic model capable of achieving a sustainable development that is inspired by the natural ecosystem functioning [2]. Indeed, the CE has been recognized by the scientific community as a transformation process of production and consumption modes requiring a series of changes and reconfiguration of the techno-economic

systems [3], [4]. The international Ellen MacArthur Foundation (EMF) defines the CE as “a new economic model that aims to decouple global economic development from the consumption of limited resources. The circular economy responds to the pressing resource-related challenges facing companies and countries, and has the potential to generate growth, create jobs, and reduce environmental impacts, including carbon emissions” [2]. According to the French government, the circular economy aims to move from a linear model in which everything becomes waste to a model in which these wastes (outputs) of the model can be converted into raw materials (inputs)¹. One of the most recognized practices of this model is remanufacturing. It's an industrial process of returning used or worn-out products to an “as new” functional state [5]. In other words, it aims to take a product at the end of its useful life, introduce it into an industrial process in which all its parts and components must be disassembled, cleaned, repaired, or replaced, and reassemble it into a product that guarantees a quality and useful life equal to or greater than that of the original product [6]. Nowadays, remanufacturing is endorsed as one of the circular economy end-of-life strategies with the least environmental impact [7].

This paper aims to perform a comparative study between traditional manufacturing and remanufacturing, through the study of a specific product to examine whether the CO₂ emission reductions between these two manufacturing strategies are significant. A search for methods to compare remanufacturing and traditional manufacturing in terms of CO₂ emissions was carried. It shows a lack of this type of research, there are no more than ten articles with comparable objects of study. Consequently, a comparative approach for assessing the CO₂ emissions of remanufacturing in relation to traditional manufacturing will be proposed. Section II presents a dedicated literature review on the topic, followed by our proposed Methodology in Section III. In Section IV,

¹ Ministère de la Transition écologique (2020). [L'économie circulaire](#)

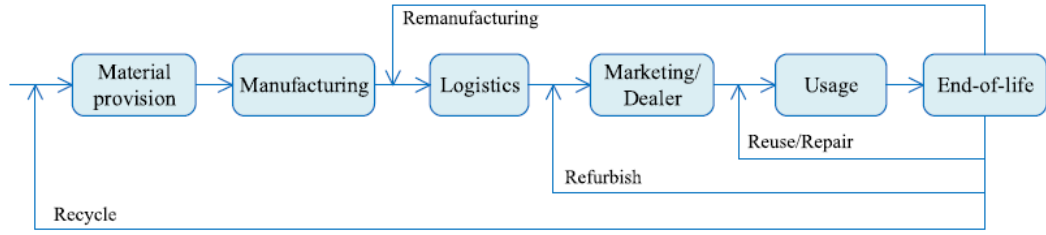


Fig 1. Different end-of-life disposal strategies in the product's life cycle [10]

we present the results based on a case study before ending with conclusions, limitations and future perspectives for our work in Section V.

II. LITERATURE REVIEW

A. Remanufacturing, a circular economy strategy

The circular economy aims to be a restorative and regenerative economy of environmental goods [8]. Thus, it improves resource efficiency by eliminating the notion of waste and allowing for a circular and restorative flow of resources, in contrast to the current linear “extract-make-discard” model that aims to consume the cheapest and most accessible materials and energy [9]. With this in mind, several strategies have emerged, including recycling, refurbish, reuse, repair and remanufacturing (Fig.1).

As mentioned earlier, this research focuses on remanufacturing which aims to restore a used product to a “like-new” level of performance [6]. It relies on a set of technologies, tools and knowledge, based on methods to recover and reuse functions and materials from industrial waste and end-of-life products, under a perspective of circularity of the economy [11].

Unlike the traditional manufacturing process, the remanufacturing process requires a preliminary inspection activity leading to the evaluation of the remanufacturability

of the products. Subsequently, these products are de-screened, sorted, cleaned and refurbished [7].

B. Comparison of Manufacturing/Remanufacturing CO₂ Emissions Models

A review of the scientific literature on Scopus was conducted to identify if there were any methods available to compare CO₂ emissions between remanufacturing and traditional manufacturing. Since 2011, 28 articles have addressed this issue. A thorough review of these articles resulted in seven relevant articles comparing similar products, either metallic or of similar dimensions [12]–[18]. It was decided to include cases comparing remanufacturing versus other practices different from traditional manufacturing were also included. The table constructed is intended to show the study conditions (comparison case, object of analysis, location, years), methods, and tools. In addition, columns on the life cycle assessment phases included in each study were included to find differences in the study boundaries of each object.

All the cases listed in the TABLE 1 below use life cycle analysis as a method of environmental impact assessment in terms of carbon footprint but differ in the tool and in the source of emissions data. Coincidentally, the most recent articles use process-based analysis and GaBi software as the source of emissions data. In contrast, the older ones use a general life cycle inventory method and SIMAPRO software. As an exception, one article uses a different source: E Balance.

TABLE 1: COMPARISON OF SCIENTIFIC ARTICLES

Reference	Practices to compare	Product	Functional Unit	Place	Tool	Data Sources	SYSTEM BOUNDARY			
							Use	Transport to customers	Manufactured product final disposition	Production of raw material
[6]	M vs RM	Loading machine	5T/8 years	China	PBA LCI	Gabi				
[7]	M vs RM	Metal cylinder	Metal cylinder	China	PBA LCI	GaBi				X
[8]	M vs RM	Metal cylinder head	Metal cylinder head	China	SLCI	E Balance 2.0				X
[9]	RM vs others	Inkjet cartridges	5 use cycles	NI	SLCI	Simapro	X	X	X	
[10]	RM vs others	Engine	NI	Italy	SLCI	Simapro	X			X
[11]	RM vs others	Air compressor	3k M ³ 7,5 bars	Brazil	SLCI	Simapro	X		X	NA
[12]	M vs RM	Diesel engine	300 km	China	SLCI	Simapro	X			X

PBA: Process-Based Analysis

LCI: Simplified Life Cycle Inventory

M: Manufacture

RM: Remanufacture

NI: Not Information

NA: Not Apply

Two articles, [12] and [18] present case studies on the comparison of the carbon footprint between remanufacturing and multi-piece manufacturing scenarios. Two other papers, [13] and [14], conducted a study on a one-piece product made from a single raw material. Therefore, the analysis is difficult to compare with our case study. The remaining articles [15]—[17] are cases comparing remanufacturing versus scenarios other than manufacturing, for which the definition of the boundaries of the analysis and the life cycle stages included could not be similar. Therefore, [12], [18] seems to be more suitable for our case study. Interestingly, these authors don't perform a piece-by-piece analysis, but instead both attempts to quantify all materials by total weight in each product and it is on those material totals that they performed the study. However, both articles differ in the construction of the boundaries of the cases to compare and the phases of the life analysis to include and even do so in the source of emissions data and the tool they use. Although several authors state that the largest remanufacturing industry is in the United States, none of the articles found is developed in that country. On the contrary, it is observed that most of the studies are conducted in China. In the case of the European Union, only one case study is presented in Italy. Furthermore, according to TABLE 1 and its subsequent analysis, it seems that there are no literature documenting cases of remanufacturing.

From this literature review, it is possible to state that although the remanufacturing process is something already documented in the literature, there are, however, no clear methods to quantify the benefits offered by this type of production compared to traditional manufacturing, specifically in terms of carbon footprint for a product like ours (metallic and multipart). This is due to the complexity that can be involved in collecting information for complex production systems and the lack of accurate assessment methods [18]. Therefore, it is interesting to implement a comparative approach of the CO₂ emission assessment for a traditional manufacturing case versus a remanufacturing case in the French reach mower sector. The work to be done will consist in checking if the approach presented in the articles of [12] and [18] can indeed give a partial solution and if it is correct how it could be adapted to the case of this study. Additionally,

a way must be found to delimit our two comparison cases, define the life cycle phases to be included in the calculation and the level of scope for each of them. This methodology must use the most appropriate tool and source of emissions data.

III. RESEARCH APPROACH

The aim of this research is to show that remanufacturing, which is one of the strategies applicable in the implementation of a circular economy, makes it possible to act on the CO₂ impact essentially at the level of extraction, importation and use of raw materials, as well as energy consumption and waste emissions. Indeed, by remanufacturing, the principle of reusing certain elements also has a very positive impact on the amount of waste generated.

The methodology presented here is divided into three main steps: (i) the description of the problem, (ii) the definition of the scope of the study and (iii) the comparison between the two cases. The proposed research approach is applied to a case study.

A. Description of the problem

In this part, the objective is to compare two machines (one new and one remanufactured) in terms of environmental impact (CO₂ emissions) throughout the life cycle of these machines. Thus, this step aims at understanding how the manufacturing and remanufacturing flows are organized in order to have a more precise vision of the problem.

B. Definition of the system boundary

To better define our study object, the first step is to define which gas(es) will be studied. Here, a particular attention is paid on CO₂ emissions, as a major gas in the phenomenon of global warming linked to human activities (CO₂ is the gas which represents more than 60% of the greenhouse gases). Our hypothesis is that CO₂ emissions, although not representing all the environmental impacts of a product, gives

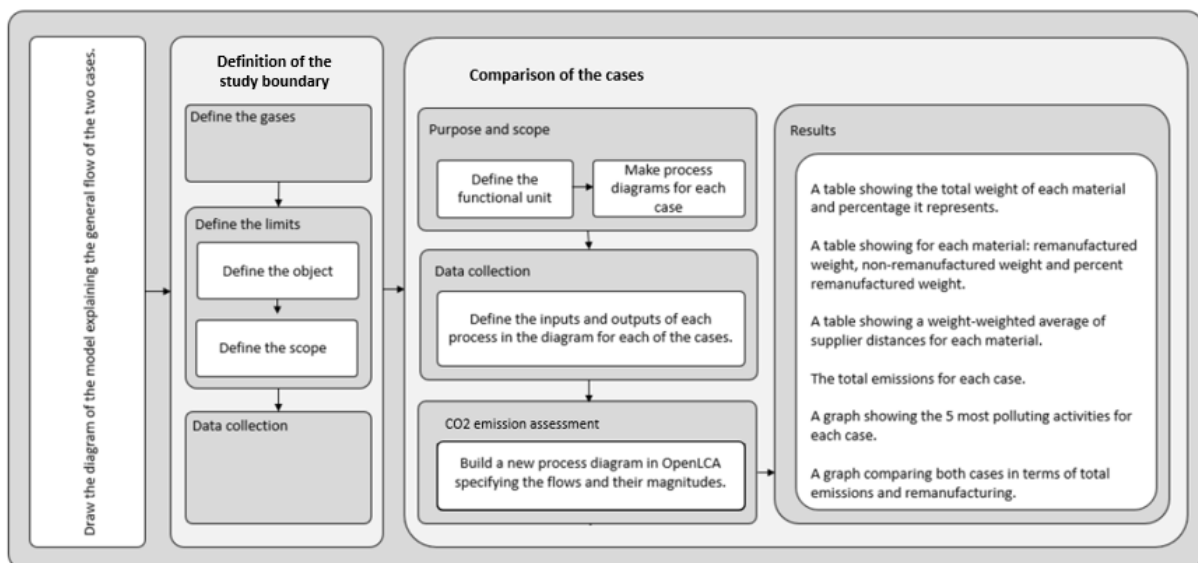


Fig 2. Graphical summary of our approach

a good picture of its influence on greenhouse gas emissions and therefore on global warming. It is a worldwide key theme, monitoring by the IPCC and subject to annual conferences bringing together all the countries of the world (Climate Change Conferences) for more than 25 years.

Once the greenhouse gases to be studied have been defined, the boundaries of analysis must be defined. This consists in defining the object and the scope of the analysis.

Defining the object of the analysis consists in defining the product to be studied. It is to study the same product, one traditionally manufactured, the other remanufactured.

The purpose of defining the scope of the analysis is to delimit the extent of the analysis to be performed. At this stage, it is necessary to identify the life cycle stages to be considered in the analysis (extraction, production, distribution, use and final disposal). If we consider that we are talking about a circular economy model in which the final disposal of resources is relevant for the analysis, all phases of the life cycle should be considered. However, we must consider that we are talking about a comparative model of two cases where the final objective is to know a percentage of reduction. Therefore, the model constants and life cycle stages common to both cases can be eliminated from the model for simplification purposes. It should be noted that the definition of remanufacturing ensures that the extraction and production phases are distinct and cannot be eliminated in any way.

Then, a data collection stage is required to prepare the comparison of the two studied products.

C. Comparison of the cases

The first stage is to define the functional unit and make process diagram of each case. The second stage consists of data collection. We define the inputs and the outputs of each process in the diagram for each of the cases. In a life cycle assessment, we must look at the overall environmental impacts in each of the stages; this concerns the depletion of natural resources (water and material), air, water and soil pollution, the evolution of biodiversity, greenhouse gas emissions.

Software for estimating CO₂ emissions is used here. Although TABLE 1 shows that there are several software packages capable of doing this work, the OpenLCA software and the associated Ecoinvent database were preferred because it is the only professional life cycle assessment software that allows for CO₂ emissions estimation that is freely accessible and available on the Internet. So, in our last stage, we build a new process diagram in OpenLCA specifying the flows and their magnitudes. The software can find for each flow (input or output) and each process a CO₂ emission in the database (Fig 3).

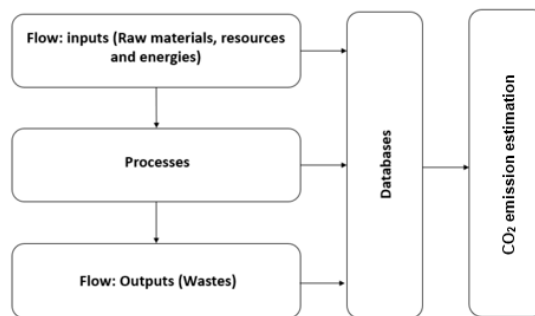


Fig 3: Operation of the software

The results therefore present (i) the material composition of the machine, (ii) the percentage of remanufacturing on that machine, and (iii) a weighted average of the distances between suppliers for each material. From these elements, the total CO₂ emissions of each product can be obtained by highlighting the most CO₂ emitting activities for each case. Finally, the results for each case can be compared to identify the reductions generated by remanufacturing.

IV. RESULTS

This study focuses on mowing machine. It is a hydraulic arm composed mostly of steel (Fig 4). It is used for the mowing of the roadside (verges, ditches and slopes).



Fig 4. Presentation of the mowing machine

Both cases are within a system that has as inputs: raw materials, resources, and energies, and as outputs: emissions, wastes and the product. The remanufacturing case (Case 2) differs from the manufacturing case (Case 1) in that it has a new input: the used product coming in reverse logistics from the customer. The fig. 5 illustrates the most common case, in which the manufacturing company is the one that recovers the end-of-life product and redirects it to the remanufacturing company. There may also be cases where the remanufacturing company recovers the end-of-life product itself. There are even cases where both companies are one and the same. These variations are supported by the model.

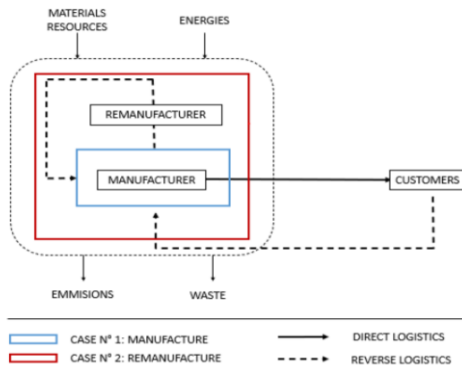


Fig 5. Comparison model of remanufacturing vs traditional manufacturing cases

A representation showing all the operations required to build the product, from the extraction of the raw materials to the final disposal of the product, as shown in Fig 6.

It emphasizes that the manufacturing case is a linear system with clearly defined start and end stages. In the remanufacturing case, since it is a circular system, a beginning and an end must be defined. It is recommended defining the beginning as the recovery of the object at the end of its life and the end as the final disposal of all waste from the system. In this way we ensure that the case is complete and considers all the processes necessary to be comparable to case 1. In this figure, the operations common to both cases are represented in gray.

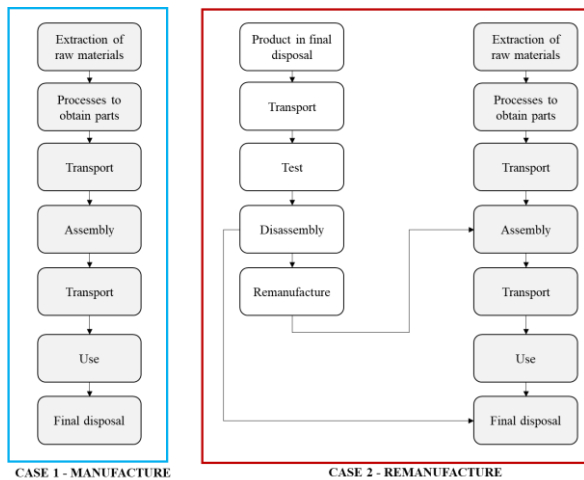


Fig 6: Comparison of manufacturing and remanufacturing operations

Some assumptions are made in order to define the boundaries of our study:

- A1.** The remanufactured product and the traditionally manufactured product will have the same quality, the same shelf life and will be used by the same customers.
- A2.** The raw materials are transported in diesel trucks.
- A3.** The mechanical operations on the metals have the efficiency of 70%. This means that for every 10 kilos of metal produced, 7 kilos will be finished parts and 3 kilos will be metal chips.
- A4.** Low energy activities not standardized in the database (assembly, disassembly, testing) have negligible energy consumption compared to other model activities: large transport, foundries, metal production, machining operations.

The functional unit, here the mowing machine, is composed of 1229 total parts with a total weight of 1882 kilograms it consists of 9 types of materials, as shown in TABLE 2.

TABLE 2: MATERIALS IN THE MOWING MACHINE

Material	(%)
Steel	78,06
Cast iron	11,39
Oil	5,90
Rubber	2,34
Plastic	1,84
Aluminium	0,09
Paper	0,05
Bronze	0,04
Zinc	0,02
Unidentified	0,40

The material of 99,60% of the weight of the machine has been identified. The remaining unidentified material (cables, buttons, etc.) will not be considered in this work because it does not represent more than 0,4%. For each of these parts, the question of their remanufacturability arose. Discussions with the company helped to determine this. The results are presented in TABLE 3. It can be seen that only three all-metal materials (steel, cast iron and aluminum) are remanufactured. All other materials, even if not remanufactured, are recovered by recycling.

TABLE 3: REMANUFACTURING BY MATERIAL

Material	Remanufacturing (%)
Steel	89%
Cast iron	100%
Oil	0
Rubber	0
Plastic	0
Aluminium	54%
Paper	0
Bronze	0
Zinc	0

In addition, 82 machine part suppliers were identified. These distances are shown in TABLE 4.

TABLE 4: AVERAGE DISTANCES FROM SUPPLIERS BY MATERIAL

Material	Average distance (km)
Steel	378
Cast iron	211
Oil	362
Rubber	195
Plastic	443
Aluminium	500
Paper	393
Bronze	27
Zinc	152
Unidentified	371

According to the method used, the traditional manufacturing of the studied mowing machine emits about 3 tons of CO₂, which would be equivalent to a round trip from Paris to Rio.

72% of these 3 tons (2.16 T) are the product of the production of steel as raw material (not to be confused with the finished steel parts). 18% (0,54 T) are the result of the mechanical operations necessary to transform the steel into final parts to be assembled in the machine. 6% (0,18 T) is the product of the production of the cast iron. 4% (0,12 T) to the whole transport (raw materials and finished parts). In this case, 90% of the emissions are directly related to the production of steel parts for a machine whose total weight is 78% steel parts. 6% of the model's emissions are due to the production of cast iron in a machine that contains 11% of its parts in cast iron. 4% of the emissions correspond to the transport operations of a machine that weighs 1.8 T and whose parts come from France, England, Germany and Italy with average distances of up to 500 km. Fewer than 1% is attributable to other activities.

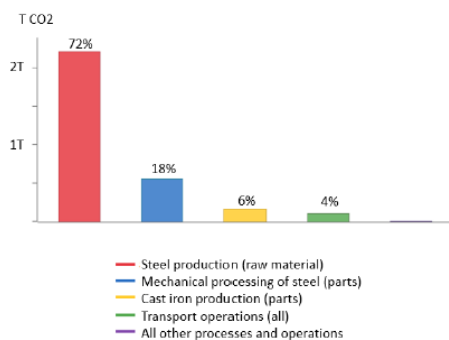


Fig 7. Graph of the 5 most polluting activities for the manufacturing case

According to the method used, the remanufacturing of the mowing machine studied emits about 0.6 tons of CO₂, which would be equivalent to a round trip from Paris to Tunis. In this case, 48% (0.29 T) of the emissions are due to transport operations. 40% (0.24 T) are due to the production of steel as a raw material. 10% (0.06 T) are due to the mechanical operations to transform this steel into finished parts ready to be assembled. 2% (0.01 T) corresponds to the rest of the activities. The transport operations appear as the most polluting, in particular because it considers the transport of the machine at the end of its life (300 km on average) from an average distance in France to the case of reconditioning (1.8T). In the case of remanufacturing, the production of the raw material steel (second most polluting activity in the case 1 model) is reduced by 89% and therefore also the mechanical operations to obtain finished parts. The production of cast iron (the third most polluting activity in the manufacturing model) disappears in the remanufacturing model because its remanufacturing is 100%.

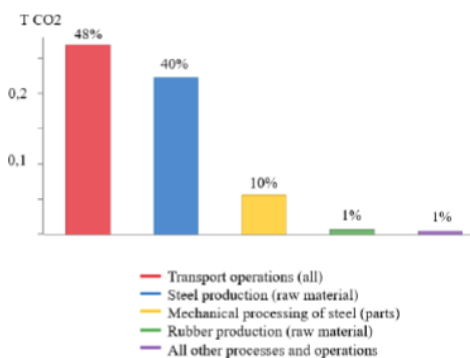


Fig 8: Graph of the 5 most polluting activities for the remanufacturing case

The comparison between these two cases shows that the reductions in CO₂ emissions reach 80%.

V. DISCUSSION AND CONCLUSION

There are examples in the literature of estimating the CO₂ emissions of products such as metal parts, air compressors, coffee machines, etc. These products contrast with the high complexity of the product in our study. The studied machine consists of 1229 parts made of 9 different materials. These parts are very different from each other. For example, the largest part represents 15% of the total weight of the product, while the 285 smallest parts do not represent more than 1%. In this project, we wanted to analyze this product in a global way, reaching an analysis level of 99.6% of the total machine. In order to do this, several assumptions had to be made to enable the comparative model to be carried out. However, these assumptions generalized the model and thus the results lost accuracy. A good addition to this project would be to perform a detailed study of the largest parts of the machine (1–5) that correspond to steel and cast-iron parts. This would provide much more accurate values of remanufacturing impacts per kilogram of steel or cast iron. The next step in this project could be to perform the same life cycle analysis and CO₂ footprint calculation for non-slash product waste processes. We could also imagine to perform a complete Life cycle Assessment considering all the themes we cited in III-C as depletion of natural resources (water and material), air, water and soil pollution, evolution of biodiversity, emissions of all the greenhouse gas. It can be concluded that the company's renovation activity has effectively reduced the environmental impact. The comparative model proposed by our methodology not only gave insight into the reduction of CO₂ emissions, but also provided these values with a reference value that makes them comparable and therefore more meaningful to stakeholders.

The definition of a methodology for calculating the CO₂ footprint was necessary because the methodologies already documented were not suitable for our industrial case. The purposes of the various studies are not comparable to ours, and those that might be do not specify the methodology used. The process-based life cycle inventory is a good tool for collecting information in our partial life cycle assessment for this case. It took such a complex product (1229 parts of 9 different material types and sizes) and transformed it into 9 raw material streams. The comparative model developed in this study can be applied to remanufactured products in the company as long as they contain a large number of parts of different material types and for which we have access to all the information allowing the mapping of the product. It is possible to conclude that the company is in a Circular Economy process and improve its CO₂ emission impact by choosing remanufacturing strategy.

VI. ACKNOWLEDGMENT

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