Environmental benefits of remanufacturing: the case study of truck injector

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ENVIRONMENTAL BENEFITS OF REMANUFACTURING: THE CASE STUDY OF THE TRUCK INJECTOR

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Abstract

Current business models base their activities on the manufacturing, distribution and selling of industrial products with a single use phase. But now, products with multiple use phases have to be considered regarding new economic and environmental pressures. Therefore, the related complex life cycles of (re)manufactured products have to be modelled and assessed by design teams for a better understanding of their overall performance. This paper focuses on the remanufacturing strategy. The study shows how to establish environmental assessments for remanufactured products life cycles and how to compare them to environmental assessments for "classical" life cycles. The final objective is to provide easy-to-use methods and tools for designers to allow them to quantify the environmental benefits related to the use of a closed loop strategy. The approach is illustrated by a case study from the industry: the truck injector.

Keywords

Life Cycle Assessment, Remanufacturing, End of life scenarios

1 INTRODUCTION

In the last decades, the introduction of the environmental dimension into the product design process became a necessity and different regulations appeared. Nowadays, everyone agree that the natural resources and the energy resources will be depleted in a medium term. So, industrial nation are now persuaded to reconsider the way they produce and consume for a sustainable development. Sustainability is defined as: "the ability of current generations to meet their needs without compromising the ability of future generations to meet their own needs" [1]. This concept is based on three pillars: environmental protection, economic growth and social equity.

Actually, there exists an enormous interest to define new strategies for sustainable development, whether it involves precious material for recycling or the reuse of components with high added-value. But we also have to consider products that are quickly obsolete from the market point of view, because they often remain functional. Industrials, confronted to the market pressure, with customers who always want better technologies, generate more and more products with an accelerated obsolescence. But most of the components in those products could be reused in a manufacturing process for new products. In that case, strategies as remanufacturing could help those new approaches. Actually, those remanufacturing strategies have demonstrated their economical interests but they have now to demonstrate their environmental interest. To make it possible, the related complex life cycles have to be modelled and assessed by designers' teams for a better understanding of their whole performance [2].

So, this paper focuses on the remanufacturing strategy. The remanufacturing process aims at extending the life of products by diverting products to a new second life instead of being buried [3]. The economic interest comes from the fact that the added value due to the initial production of the product is preserved fully or partly. The environmental interest comes from the lower energy and raw material consumptions compared to the manufacturing of a second new product. Therefore by keeping the components, material extraction and energy consumption can be reduced but, it is necessary to assess the whole life cycle to verify that environmental impacts don't increase by the use of remanufacturing processes or by transportation.

This study shows how to establish the models and how to compare the environmental assessments of remanufactured products life cycles vs. classical life cycle scenarios. The final objective is to provide easy to use methods and tools for designers to allow them quantifying the environmental benefits related to the use of a closed loop strategy. In this project, a Life Cycle Assessment [4], life cycle bricks [5], 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 disposal scenarios. The approach is illustrated by a case study from the industry: a truck injector.

2 LITERATURE REVIEW.

The current literature shows that there is a growing interest in the remanufacturing of product as an end of life scenario [6] [7] . In 2002, Ijomah [8] defines remanufacturing as "the process of returning a used product to at least Original Equipment Manufacturer original performance specification from the customers' perspective and giving the resultant product a warranty that is at least equal to that of newly manufactured equivalent". The literature covers several fields like: the design for remanufacturing and the evaluation of the products remanufacturability [9] [10] [11], the remanufacturing operations (disassembly, cleaning, inspection and sorting, reconditioning, reassembly) [6] [7], the environmental impacts analyses [12] and economical analyses [13] [14].

In 1997, Gungor proposed an algorithmic method to obtain an optimal sequence of disassembling [15] but this method does not consider the economic and environmental aspects. However at the beginning of the 2000's some researchers [16] [17] focused on how the disassembly of products could be optimized.

In disassembly operation an important issue is the time required to dismantle a product, this time depends on several parameters as the joint types, product architecture, etc. The time to dismantle is also linked to the number of components; that also could increases the complexity of the operation. According to Kara [18] completely dismantling a product in the shortest possible time is too expensive due to a lack of technical's constraints. Zuidwijk says "a product recovery strategy determines the degree of disassembly of a product and the assignment of recovery options" [19].

A new research field in design emerged in response to the need for making dismantling profitable: "Design for Modularity". The modularization of products is the first step for sustainable design [20]. Modular products make it possible to improve valorisation of materials by differentiating the modules which can be recycled from the modules which cannot be recycled [21]. The design of future products must reflect the definition of the modules and architecture.

Remanufacturing allows reusing products or modules in several phases according to customer requirements or market evolution [20]. Tomiyama proposes a concept, "Post Mass Paradigm Production" [22] to reduce the consumption of natural resources as well as the production of waste while maintaining the standard of living at current or higher levels. The satisfaction of this new model passes by an increase of products lifetime, posing the problem of functional obsolescence. The increase in the product's usage time and thus the limitation of obsolescence incorporate a specific strategy according to the value of the component (repair, update, reuse, etc.). "Longer-life products should have functional upgradability besides reliability and fault-tolerance" [23] [24].

Gehin [12], proposed a product model using the strategies of revalorization of the components in several use cycles. His approach allows an environmental evaluation of a product according to these modules, but considering several use cycles imposes operational costs (Supply chain, refurbishing, etc).

A study done by Farrant et al. 2010 [25], shows us the environmental benefits of "reusing", with a simple product "clothes" that have not so many components. The LCA methodology is used to compare clothes are disposed to incineration and clothes that are collected in order to be reused.

No papers were found reporting comparative LCA assessment for product with several components or for product with components able to perform several usage phases.

Although remanufacturing seems to be a sustainable strategy, there must be an approach to prove it. In the following section, the model, tools and method proposed to do those kind of assessment are described. The truck injector case study will be developed in the next section.

3 AN APPROACH FOR THE LCA OF REMANUFACTURED PRODUCTS.

Remanufactured products differ from classical products because of the number of usage phases they can realise. To establish comparative LCA for remanufactured products life cycles and classical life cycles (cradle to grave) it is necessary to propose a specific life cycle model with a parameterisation of some indicators. To help designer to make decision, it is also necessary to provide tools that can support the whole evaluation process.

3.1 The Life Cycle model and its parameterisation for remanufactured products

The remanufacturing process is a process in which reasonably high volumes of similar products are collected to a central service place, disassembled then treated to be reused [26]. In some cases, the final product can be upgraded but in this paper will focus on a "basic remanufacturing" that means : *an industrial process which aims to recover a used/broken-down product (or component) to the same performance level calculated at the design process and developed by the fabricants in order to accomplish a use lifecycle phase* [27].

The remanufacturing process is generally composed of several stages: disassembly, testing, repair, cleaning, inspection, updating, component replacement and assembly [28] [29]. At each stage, specific measures guarantee quality control. But here the complexity of the LCA is not related to these processes stages but to the links between the phases of the product life cycle. Indeed, at the end of the usage phase, each product component can be reused, remanufactured, recycled, incinerated or landfilled. That means there are numerous possible combinations compared to a linear classical model.

The model (Figure 1) inspired from Gehin [12] can be used to model as much scenarios as possible. A classical life cycle can be obtained as well as very complex scenarios using a mix between reusing, remanufacturing or recycling. Lifecycle phases have been defined, depending on the designers' expertise in being able to consider the real causes of the environmental impacts. So, 8 generic phases have been used to model the lifecycle from a designer's point of view: 1) Material Extraction and Transformation, 2) Component Manufacturing and Assembly, 3) Component Distribution, 4) Product Assembly, 5) Product Distribution, 6) Product Use, 7) Product Take-back, 8) Component end-of-life with 5 options (reuse, remanufacturing, recycle, incineration, landfill). All the people involved into the product design can use this model to fill in their own data (engineering, supply chain, recovery…) with an integrated manner and a common goal. Then, with that model, designers are able to represent and to design the product life cycle while designing the product itself.

To establish the common ground for the integration of all the actors, it is also necessary to define adequate parameters inside the model. Those parameters are established by the team and their values would depend on the designers' choices. The common definition of those parameters during the design process is necessary to avoid time consuming in the product redesign during the detailed design. Here are; for example, different parameters that could be considered in the lifecycle of the assessed product:

- **the "number of use phases" of the product**. It can be deduced from the technological choices made for the product during the design process or from the marketing enquiries. But this parameter also impacts other processes (i.e. reverse logistic, production) that could affect the final decision. So it should be optimised while considering the whole life cycle.
- **the number of products/components recollected in the reverse logistic model**. Because of the recovery options and because of the customers' habits, the number of remanufactured products is usually less that the number of product initially produced. In some cases, it is necessary to consider this parameter and to increase it while improving the manufacturer collection model. (i.e. Product Service Systems strategies or standard exchange policies)

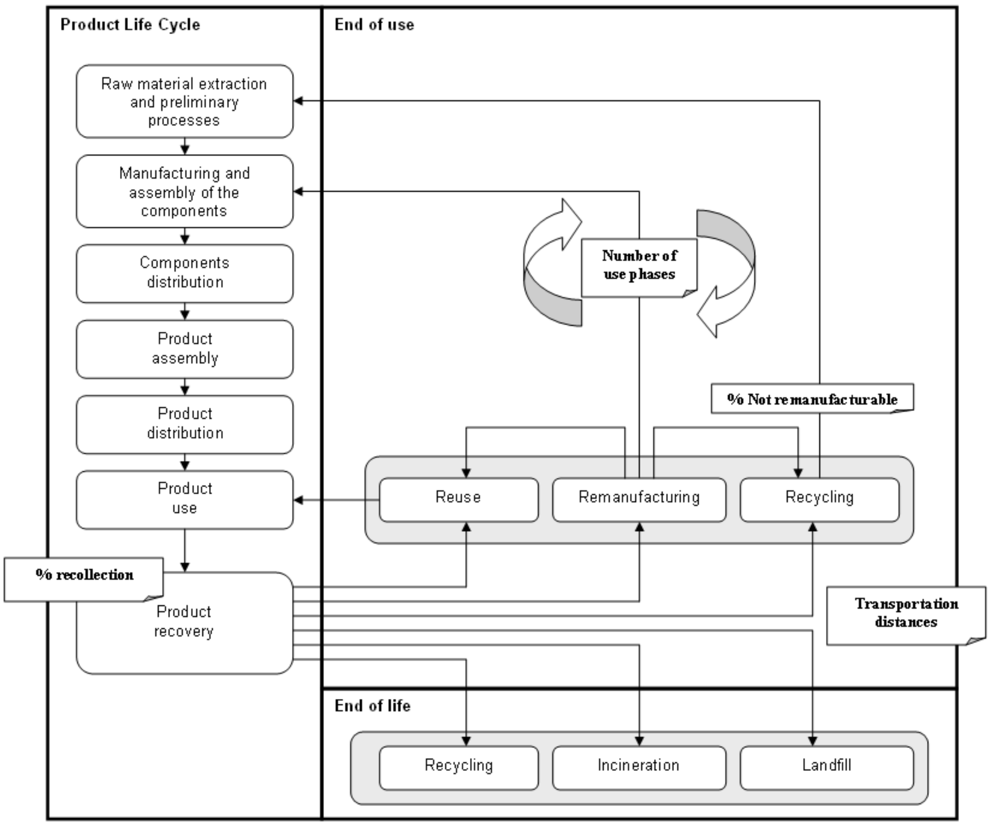

Figure 1: Product – multiple use cycle phases approach

- **the number of products not remanufacturable**. Several tests must take place in the recovery of material, components or products. Those punctual tests during the remanufacturing process force us to consider a "percentage of rejected products" (e.g. products that can't be disassembled, products with modified mechanical properties, non repairable products …).
- **the transportation distances**. All the activities used in the reverse logistic must be optimized regarding the product and the supply chain characteristics. An improvement can be done on the both to minimize environmental and economical costs.
- …

This is a non exhaustive list, depending on the product under study.

3.2 Tools and method to measure the environmental benefits of remanufacturing strategies

How to evaluate closed-loop strategies from an environmental point of view? A qualitative method such as an LCA is necessary to give precious indicators to designers also at the beginning of the project with rough representations of the product and of its life cycle. In that case, LCA are recommended to give first orientations to the design project. But the current tools don't really support the closed loop analysis. They are well adapted to linear life cycle models but are really time consuming when you want to test many closed loop strategies with different options (number of use phases, rate of broken products,…). So, there is a gap today between the existing designers' tools and their needs for products closed loop life cycle environmental impact evaluations. The software CLOEE (Closed Loop Environmental Evaluations) can be used to help those evaluations. It is a calculation sheet developed by the informatics department at the G-SCOP Laboratory.

This software allows to consider different recovery strategies for components in a product taking into account several usage phases. It helps the designer to create different life scenarios for products under design and provides the comparisons between the environmental impacts for the different designed life cycles.

To obtain results, the following steps must be followed:

- Define your product and the related life cycles. For this, it is useful to use the previous life cycle model that give you the ability to make as much as scenario you want and that give you the ability to change parameters for the product life cycle
- Calculate the impact assessment of the life cycle bricks. A life cycle brick is defined as a black box containing the necessary data for the calculation of environmental impacts according to the Life Cycle Impact Assessment methodology.
- Each brick contains:

  - an identifier, based on the name of the lifecycle phase and the component or product name
  - data related to the components or product and relevant to the lifecycle phase: mass, type of material used…
  - the processes related to the lifecycle phase, and for each of them the consumption and impact towards the environment
  - the results of the environmental impact assessment after there evaluation.

- Enter the data in CLOEE (products, scenarios)
- Define your calculation (life cycles)
- Watch and save your results established per usage phases.

Because you can model cradle to grave or cradle to cradle scenarios, you are then able to compare environmental assessments for a "classical" life cycle and for closed loop strategy including remanufacturing. The different steps of this approach will be detailed in the next section on the injector case study.

4 CASE STUDY– THE TRUCK INJECTOR

4.1 Product description

A first analysis has been realised for a product in the industry of heavy trucks: a diesel injector (figure 2). An injector is an exchangeable element inside trucks engines. Its function is to inject the right proportion of fuel/air to the engine of a diesel truck for a good combustion. The injector has a shorter life cycle compared to the truck/engine life cycle that means it needs a frequent replacement. This element of the engine is currently remanufactured (because of its economical interest) and we have now to demonstrate that this remanufacturing induced extra benefits from an environmental point of view.

All the necessary data for the present study have been collected with members of the remanufacturing site and of the reverse logistic site. Several interviews, surveys and visits have been carried out to approximate the remanufacturing model. It is important to be objective to elaborate the interviews and surveys; this helps to define the right level of required detail needs and to identify the hypothesis that have to be done. Indeed, unknown data and data difficult to find are the most common problems in the data collection process. In order to realise the assessment some unknown data can be estimated with the support and the experience of designers and of people involved in each phases. Once those unknown data have been estimated, an analysis of the sensibility of the model can be used as a solution to discard irrelevant data and to deep in the search of the relevant data.

Figure 2: Injector diesel

For this study, a representative injector has been chosen and the product data have been established (materials, weights and processes used for the manufacturing). (Table 1).

More relevant data will be presented with some examples in the section presenting the lifecycles bricks of the injector.

4.2 Remanufacturing Injector Life Cycle

To continue with the study, the whole life cycle of the remanufactured diesel injector has been realised (Figure 3). This life cycle shows each process considered in the present analysis and two parameters considered in this study: the "number of use phases" of the product and the number of non remanufacturable products.

Component	Mat.	Weight [g]	Process
Body	Steel	551	Turning, Milling Drilling
Union nut	Steel	18	Forging, Turning Milling
Cap	Steel, PET, Cooper	74	Forging, Milling, Turning Thermoform
Injector unit	Steel	25	Plastic def. Forging
Stem	Steel	22	Turning Drilling
Injector end	Steel	30	Turning Drilling
Fastening bolt	Steel	32	Forging Turning Milling

Table 1: Some component data for the injector

In the section before, it was mentioned that the life cycle of an industrial product could be represented in a simple way with eight phases. Here are presented the data included in the different phases as well as the different hypothesis made at this stage of the evaluation.

Material extraction and transformation
In that phase are considered the material necessary for all the use phases that mean the materials for the manufacturing of the initial product and then materials necessary to remanufacture the product for the other usage phases. Materials used in the manufacturing of the components is one of our uncertainties In order to overcome that barrier, the main typologies of alloyed steel that can satisfy the use conditions were reviewed. Those steel are alloyed with chromium and molybdenum. A study of the environmental impacts from different chromium-molybdenum steels was realised. Finally, the steel 42CrMo4 was retained for all the steel components because the impacts of this steel are well representative for this class of steels. For the cap, that includes a steel part but also an electric terminal with copper and a PET cap, data were found in Simapro databases.

Components manufacturing and assembly
Here are considered the processes that participate in the manufacturing of all the initial components and of the components that should be replaced in the other life cycles (turning, milling and drilling). The inputs necessary in each process is also needed, (e.g. electrical energy consumption according to the batch of production). The list of processes used during the manufacturing was roughly estimated (table 1) and the Simapro databases provide the energy data required for each process.

Component distribution
Here, the hypothesis is that the manufacturing of the components takes place next to the injector assembly site. That means there is no distribution of the components.

Product assembly
Because there is no specific treatment at this stage, its environmental impact has been neglected.

Product distribution
Here is considered the diesel injector transport from the manufacturing site to the final customer who will produce trucks engines. The injectors were considered as manufactured in Germany (Stuttgart) and transported to the middle of the France (Bourges)

Product use
The environmental impacts in the use phase of a diesel injector diesel were neglected. All the environmental impacts concerning the use are allocated to the truck.

Product take-back
The reverse logistic model is a necessary model to assess because of the environmental costs of transports. To create it, the business model of the enterprise who manufactures trucks was used. A logistic platform network supports the sales. That network counts with points in Europe (e.g. UK, Spain, France …). Reverse logistic uses those platforms to receive used and broken-down products from final customers (e.g. injectors' diesel, gear boxes, truck engines, etc.). Then, the used/broken-down products are transported from the platforms network to a central warehouse for a visual selection and a codification. Those used parts are ready to be transported to the remanufacturing site. The distance, the transports frequency, the proportion of product in a truck,…, are data provided by the remanufacturer logistics.

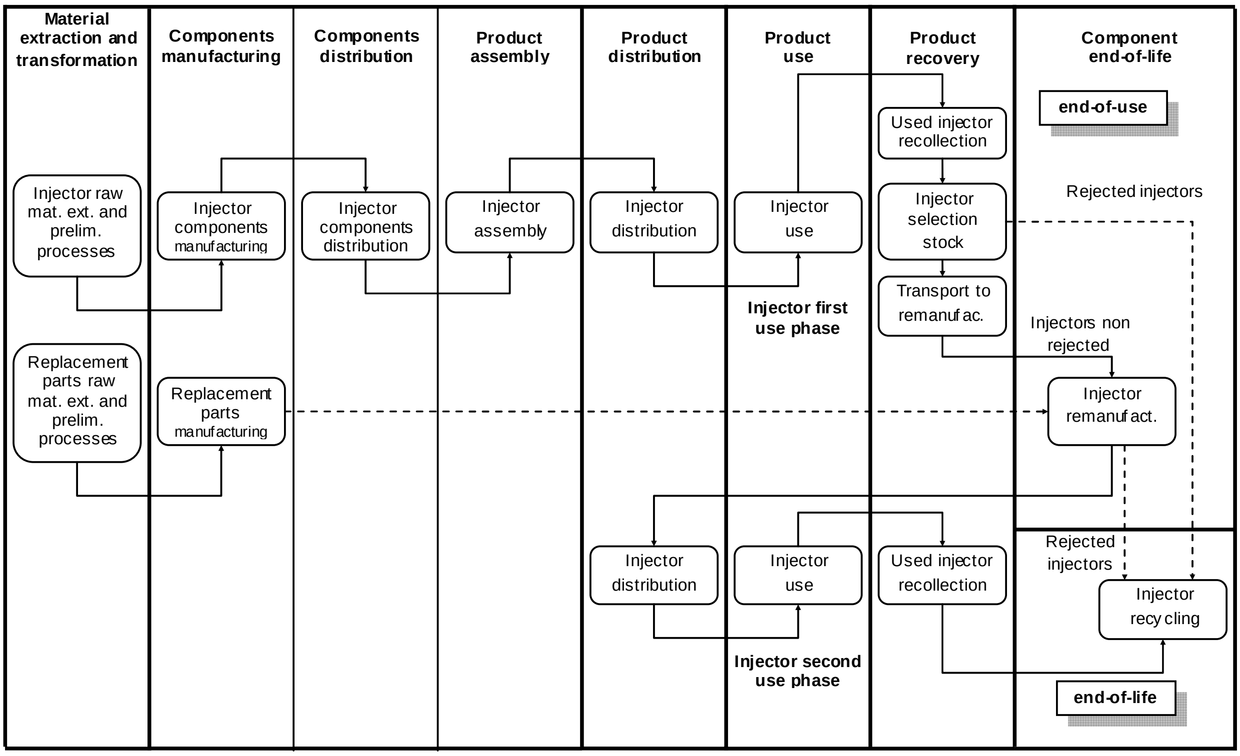

Figure 3: Injector diesel life cycle

The proportion of injectors not recollected is unknown. In fact, because there is enough collected product to supply the customers with standard exchange parts, the model doesn't take into account the percentage of recollected parts. The model considers that all the recollected products are remanufactured and then used. The other inputs at this stage have been neglected (e.g. packing material that are reusable or very limited).

Components end–of–life
As presented in the section 2.1, there are 5 end-of-life/usage options. The injector life cycle uses 2 options: remanufacturing and/or recycling. At the end-of-use of the components, all of them will pass to the remanufacturing process.

During the remanufacturing process, test are realised (e.g. pressure, injection…). Injectors that don't succeed the tests are disposed to the recycling process. The other are disassembled to replace some parts and complete the recover process of the product. All the consumptions have to be included in the remanufacturing process (e.g. electrical energy, fluids…). That information could be part of the data hardly to find. The consumptions of the remanufacturing processes were roughly estimated with the support of the engineers working in the remanufacturing of the injector. The location of the recycler industry is another data to know because this transportation is included in that life cycle phase.

4.3 Life Cycle Bricks in the Injector Diesel's Life Cycle

The life cycle inventory was realised while using the life cycle bricks model. The goal is to be able to manipulate the bricks and not a complex model of the life cycle when testing the different life cycle scenarios. An example of brick representation is given figure 4 with the life cycle brick for the "manufacturing phase" of the component "Body". On the brick, there is the name of the life cycle phase, the name of the component, the list of input data used to evaluate the environmental impact of this component in that phase (machining processes) and the output data with the values of the environmental assessment (calculated here with eco-indicator 99)
Some components have different disposal scenario (figure 5, figure 6). So, different calculations of the environmental impact were realised. For the remanufacturing case, the processes were detailed, because they do not

exist in the current databases. For the recycling, data from Simapro databases were used.

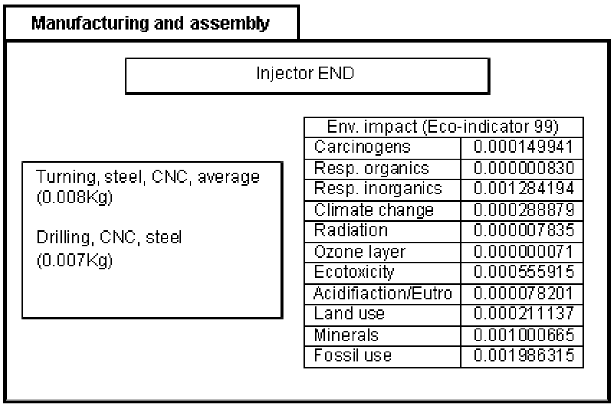

Figure 4: The manufacturing life cycle brick for the injector END

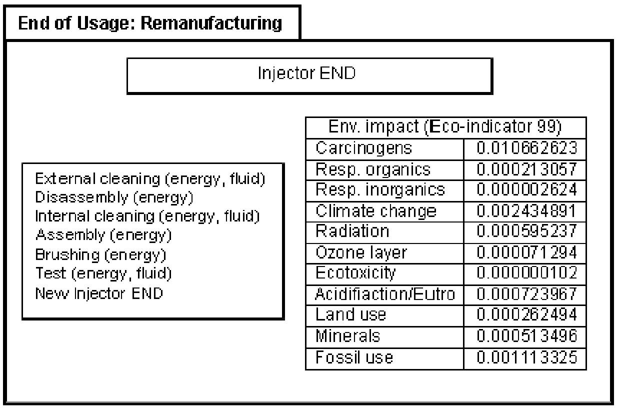

Figure 5: The remanufacturing life cycle brick for the injector END

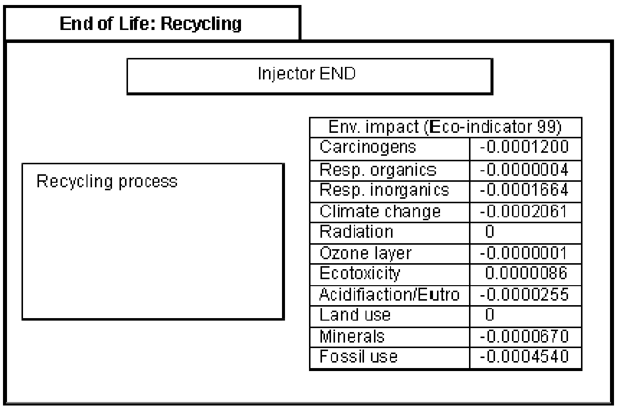

Figure 6: The recycling life cycle brick for the injector END

This assessment was done using the software Simapro, methodology Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H. An example of the assessment supported by Simapro is presented in the table 3 for the component injector's body. Each column represents the result for one life cycle brick. This table is used to fill in the data in the CLOEE software.

4.4 End-of-Life Scenarios

Once the data filled in CLOEE, it is necessary to specify the life cycle scenarios. The scenarios to be compared are presented in the table 2. Seven scenarios were tested:

- A "classical" life cycle scenario (CLC), with only one use and a recycling process in end of life.
- A remanufacturing life cycle scenario (RLC 25%), with two use phases, 5 components remanufactured, 25% of products collected are recovered and a recycling process in end of life.
- A remanufacturing life cycle scenario (RLC 75%), with two use phases, 5 components remanufactured, 75% of products collected are recovered and a recycling process in end of life.
- A remanufacturing life cycle product scenario (RLC 100%), with two use phases, 5 components remanufactured, 100% of products collected are recovered recovery, and a recycling process in end of life.
- Three remanufacturing life cycle scenario with three use phases and 5 components remanufactured and a recycling process in end of life for each scenario; the RLC 25%, RLC 75%, RLC 100%.

For each component, a scenario was filled in and calculation for each life cycle scenarios were realised.

STUDY CASES	**CLC**	**RLC (25%)**	**RLC (75%)**	**RLC (100%)**
Nb-of-use	1	2	2	2
Recov. remanf.	No comp	5 comp. of 7	5 comp. of 7	5 comp. of 7
Perfor. remanf proc.	0 %	25 %	75 %	100 %
Recycle EoL	100%	100%	100%	100%

Table 2: Scenarios analysed with CLOEE

domain	mat.	manuf.	distrib.	reuse	remanuf.	recycling	incin.	landfill
Carcinogens	0,000052293	0,000149941	0,000001483	0	0,010662623	-0,00012001	0,000127187	0
Resp. org.	0,000001408	0,000000830	0,000000100	0	0,000213057	-0,00000039	0,000000063	0
Resp. inorg.	0,000903102	0,001284194	0,000067018	0	0,000002624	-0,00016640	0,000028065	0
Climate ch.	0,000230962	0,000288879	0,000015358	0	0,002434891	-0,00020612	0,000002141	0
Radiation	0	0,000007835	0,000000143	0	0,000595237	0	0,000000018	0
Ozone layer	0,000000004	0,000000071	0,000000012	0	0,000071294	-0,00000009	0,000000002	0
Ecotoxicity	0,000145821	0,000555915	0,000008144	0	0,000000102	0,000008635	0,005049797	0
Acid/Eutro	0,000153245	0,000078201	0,000012220	0	0,000723967	-0,00002550	0,000005738	0
Land use	0,000273839	0,000211137	0,000004552	0	0,000262494	0	0,000001297	0
Minerals	0,000097125	0,001000665	0,000002214	0	0,000513496	-0,00006700	0,000000758	0
Fossil fuels	0,001622687	0,001986315	0,000267988	0	0,001113325	-0,00045407	0,000041978	0
TOTAL	0,003480486	0,005563985	0,000379233	0	0,016593109	-0,00103098	0,005257045	0

Table 3: Results of the impact assessment by phase for the component body of the diesel injector

	Mat.	Manu.	EoL	Total
CLC_1 use	0,13	0,13	-0,031	0,23
RLC_2 uses 25%	0,11	0,11	-0,024	0,21
RLC_2 uses 75%	0,08	0,08	-0,011	0,16
RLC_2 uses 100%	0,07	0,07	-0,004	0,13
RLC_3 uses 25%	0,11	0,11	-0,025	0,21
RLC_3 uses 75%	0,07	0,07	-0,004	0,13
RLC_3 uses 100%	0,04	0,05	0,005	0,10

Table 4: Results in Points (Eco-indicator 99) for the different scenarios

The scenarios considered in this analysis could be compared with the cradle to grave life cycle. Figure 8 presents that comparison. Here, it is possible to quantify the environmental benefits obtained while using the model proposed. The scenario with a second use phase and 25% of the injector recovered has an environmental gain of 10.76% 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 10% of injectors recovered, the scenario is 57.41% less impacting than the cradle to grave injector life cycle.

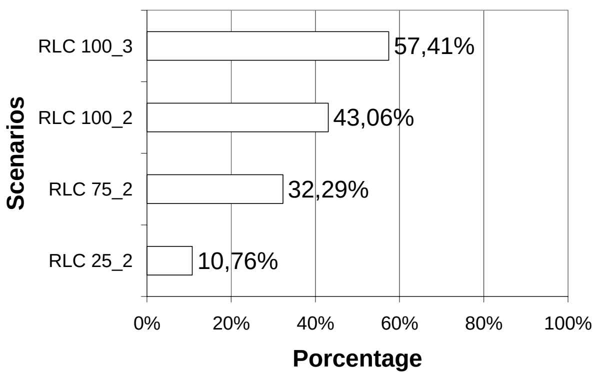

Figure 8: Benefits obtained (in %) compared to a classical “cradle to grave” life cycle for the injector

5 CONCLUSION

The methodology used allows highlighting the environmental benefits from the remanufacturing process for small trucks products. It is now necessary to apply this approach to other products remanufactured in the trucks industry to be able to help designers to make decision taking into account environmental concerns.

The design of the components (material, weight,…) plays a significant role in the product analysis. But the processes that are used all along the life cycle influence a lot the environmental assessment. So, this approach should help designers to make decision for the product design but also for its life cycle design. This approach can be used now to make decision concerning the remanufacturing of components.

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