STUDY N° 2018-02

MATERIAL LOOPS, PRODUCT LOOPS AND LCA

SYNTHESIS

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SCORE LCA is an association that has been created to financially support collaborative research on LCA and related topics. It aims to promote and organize cooperation between companies, institutional and scientists in order to support the evolution of LCA methods and its practical implementation at European and international level.

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✓ The information and conclusions presented in this document were established on the basis of scientific and technical data and regulatory and normative framework in force at the date of the publication of documents.

SUMMARY

1. Introduction

Since the launch of the action plan for a circular economy by the European Commission, measures to promote circular systems have been numerous. These measures aim to shift from a linear to a circular paradigm allowing the reduction of primary resource consumption and avoiding waste disposal. However, many types of loops exist and the ones to choose to achieve this goal are uncertain. Life Cycle Assessment (LCA) is a recognized tool to answer this question by considering environmental impacts from analyzed systems. This study is a follow up of previous SCORE LCA studies on circular economy and focuses on information provided by LCA to orientate the choice of a producer towards specific loops and on the parameters that can affect this choice.

For companies, the choice of recovery loops arises for to flows: the flows of products that they place on the market and arriving at the end of their life, and the flows of waste and co-products from their production activities. We will call the loops relating to the former the “product and material” loops and the loops relating to the latter the “waste and co-products” loops, which include industrial symbiosis systems.

The two types of “product and material” loops are open loops and closed loops. A closed loop is a system in which some or all the materials of an end-of-life product are fed back into the same system, thereby producing the same product. An open loop is defined by the recovery of part or of all the materials of a product in another production system, resulting in a product fulfilling a function different from the original product.

When a product reaches its end of life, it can re-enter a production system at each stage of production, following different recovery routes:

- **Reuse:** recovery of substances, materials or products that have not become waste (at the "end of use") for a use identical to the one for which they were designed.
- **Preparing for reuse:** any control, cleaning or repair operation conducted to recover substances, materials or products that have become waste to be reused without any other pre-treatment operation. It includes in particular:
  - *Remanufacturing:* set of processes consisting in restoring a product to obtain performances identical or superior to the original product.
  - *Refurbishing:* restoration of a product without having the objective of bringing it back to its original state but allowing its operation.
  - *Repurposing:* set of processes consisting in restoring a product into a product having functions different from the original product.
- **Recycling:** any recovery operation by which waste is reprocessed into substances, materials or products for the purpose of their initial function or for other purposes.
- **Other operations:** any other operations such as energy recovery, waste treatment for fuel production and use for backfilling operations.

Even if the waste hierarchy is a first basis to guide decision-makers towards a waste treatment process, this choice must remain based on case-by-case analyses. The following questions concerning the prioritization of recovery loops arise: *What do LCA studies teach us about the most efficient recovery loops from an environmental point of view? Can we identify contexts favoring a loop rather than another from an environmental point of view? Can we identify the modeling parameters that most determine this choice?*

The objective of this study is to provide elements of response by following two stages: a review of the literature and an analysis of six case studies.

2. Literature review – "product and material" loops

The literature review was conducted with the aim of identifying publications (report, scientific articles etc.) comparing at least two recovery loops based on LCA.

1. Context and objective of the studies

Twenty studies comparing different loops and one study comparing the slowdown of a loop with a recycling loop were identified. Most of these studies were conducted in Europe in the electrical and electronic equipment, packaging and automotive sectors. Among the 20 studies comparing loops, 69 cases of loops are analyzed, one case of loop representing a pair of one product and one loop. The recycling loops are the most studied (67% of the loops), followed by preparation for re-use (20%) and re-use (13%) loops. Open and closed loops represent 42 and 53%, respectively. The 69 cases of identified loops allow analyzing 56 pairwise comparisons. The most common comparison is that of two open recycling loops.

2. Methodological approach

Three LCA methodological approaches could be identified (Figure 1).

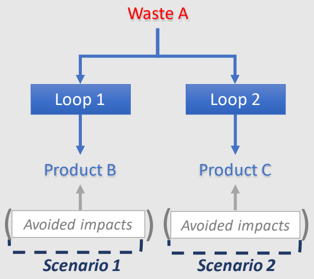
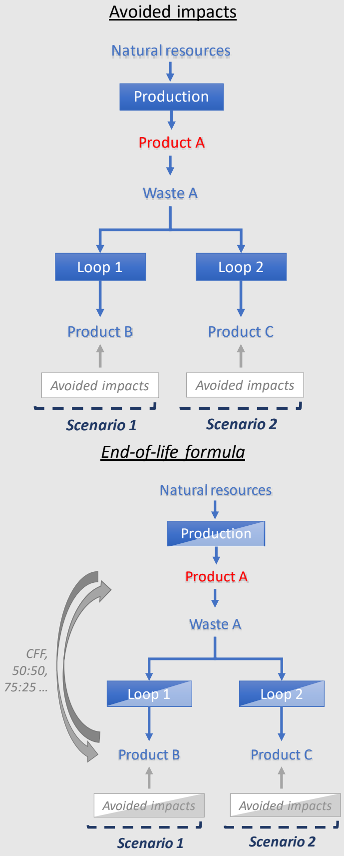
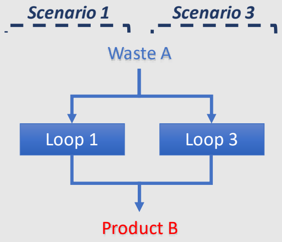
	« Waste » approach	« System » approach	« Feedstock » approach
Research question	Which loop should you choose to valorize a product at its end of life?	What is the contribution of the end-of-life management of a product to its total impact?	Which loop should you choose to produce a specific product?
Functional unit	Treatment of waste A	Production and end-of-life management of product A	Production of product B
Approach scheme			 *Remark: in this case, it is not possible to compare scenarios 1 and 2 as the compared loops must produce the same product.*

Figure 1: *Scheme representing the different approaches which can be chosen to compare recovery loops*

The three approaches were called the "Waste" (followed in 33% of the studies), "System" (40% of the studies) and "Feedstock" (27% of the studies) approaches. They are characterized by specific system boundaries and functional units and therefore by the research question they answer.

The compared loops can result in different environmental benefits. Generally, these benefits are considered by the substitution method, which subtracts the impacts avoided by the production of a new product/service from the total impact of the recovery processes. In the case of the "System" approach, an End of Life Formula (such as the Circular Footprint Formula) can also be applied. In this case, the impacts of the valuation processes and the avoided impacts are allocated to the different products from the value chain based on allocation factors.

3. Considered impact categories

The impact categories related to resource consumption are key categories to consider when analyzing systems implemented in a context of circular economy. However, the literature review shows an incomplete coverage of the impact categories related to resource consumption, which only allows drawing partial conclusions on the hierarchy of loops and their potential to increase the self-sufficiency of regions or organizations who implement them.

4. Results on the hierarchy of loops

The conclusions related to the validation of the waste hierarchy are examined. Among the 27 comparisons allowing answering this question, 21 validate the waste hierarchy, against 6 which do not.

Among the 11 comparisons comparing a closed loop and an open loop, 6 conclude on the advantage of open loops compared to closed loops, 2 obtain results which do not provide a clear answer, and 3 conclude on the advantage of closed loops compared to open loops.

Out of the 21 studies identified, 15 carried out a sensitivity analysis. Among these studies, 7 identify parameters that can change the conclusions of the study. Ten parameters contribute to changing the results on the hierarchy of loops in at least one study (e.g., the length of the first life, the choice of avoided products and the impact assessment method).

5. Conclusions of the literature review

Lessons learnt from the literature review are the following :

- Most of the cases of reuse/preparation for reuse have a lower environmental impact than recycling loops.
- For products with a large contribution of the use phase and rapid technological progress reducing the impact of the use phase, the advantage of reuse/preparation for reuse compared to recycling depends on time, as technological improvements allowing a reduction of the impact of the use phase are being made.
- Closed loops do not appear to have a lower environmental impact than open loops.
- Ten parameters that can potentially change the hierarchy of loops in the circular economy could be identified (see the full report).

3. Case studies

1. Cases n° 1, 2 and 3: recovery of permanent magnets at their end-of-life

1.1. DESCRIPTION OF THE SCENARIOS

These cases compare the environmental performance of three recovery routes for permanent magnets from wind turbines at their end of life: remanufacturing, recycling by recasting magnets and recycling by extraction of rare earth elements (REE). Figure 2 summarizes the main steps of these 3 routes (in blue the processes specific to remanufacturing, in orange recycling by recasting and in green recycling by extraction of REE). The functional unit is "end-of-life management of one ton of permanent magnets used in a wind turbine". All processes from dismantling of the wind turbine to the production of the magnets for cases 1 and 2 and REE extracts for case 3 are included in the system boundaries. A “Waste” approach is followed and the benefits from materials recovery are considered by the avoided impacts method.

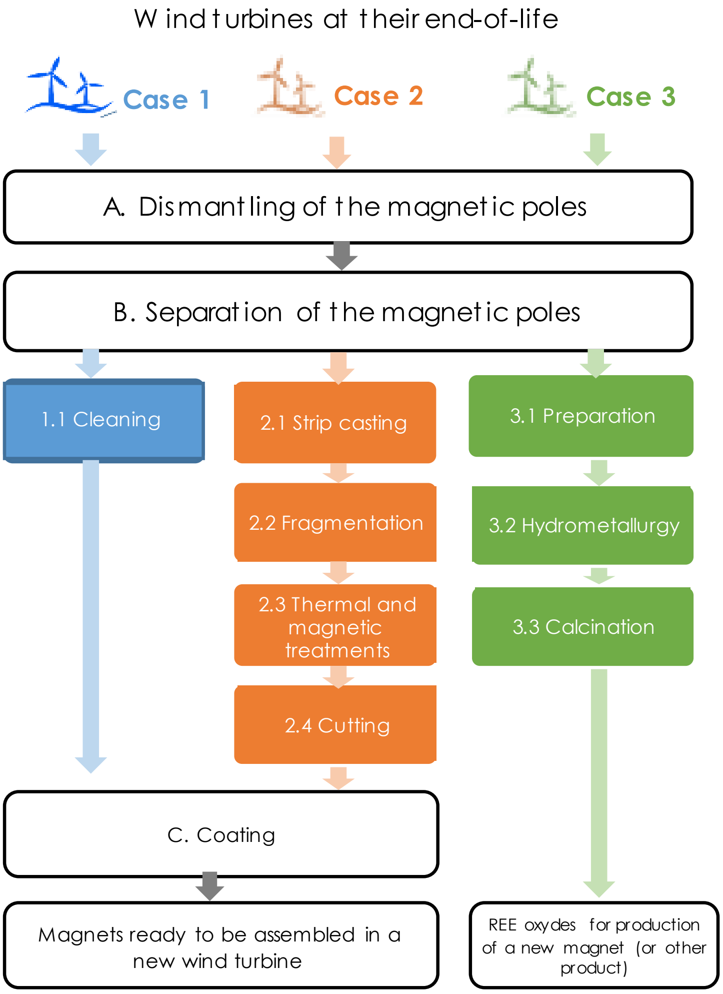


Figure 2: *Process steps of the three routes for the management of permanent magnets at their end-of-life*

1.2. LIFE CYCLE INVENTORY

The recovery processes are modeled based on experimental data from the CEA. Coating and finishing data are taken from Sprecher et al. (2014). For cases 1 and 2, the avoided impacts relate to the production of new permanent magnets in China. For case 3, the avoided impacts relate to the production of rare earth oxides from mining activities. In addition, nickel is recovered and therefore avoids the extraction of virgin nickel. In the 3 cases, the quality of the final products is the same than the products made from primary resources.

1.3. IMPACT ASSESSMENT AND SENSITIVITY ANALYSIS

The impact assessment method CML v3.05 is applied. A sensitivity analysis is carried on:

- **LCA approach:** the « Feedstock » approach is tested. In this case, the functional unit is defined as *« one ton of permanent magnets ready to be assembled in a new wind turbine »* for cases 1 and 2 and *« the production of 1 kg of rare earth oxides »* for case 3. Permanent magnets at their end-of-life are considered free of environmental burden.
- **Impact assessment method:** impact assessment using ILCD v1.10 and Impact 2002+ v2.14.
- **Inventory data for the recycling processes:** theoretical upscaling of the inventory from lab scale to industrial scale.
- **Inventory data for avoided products:** production of new magnets in Europe instead of China.

1.4. RESULTS

Remanufacturing appears to have the lowest environmental impacts. At laboratory scale, the impact of recycling 1 (recycling with strip casting) is higher than for recycling 2 (extraction of rare earth oxides) (Figure 3).

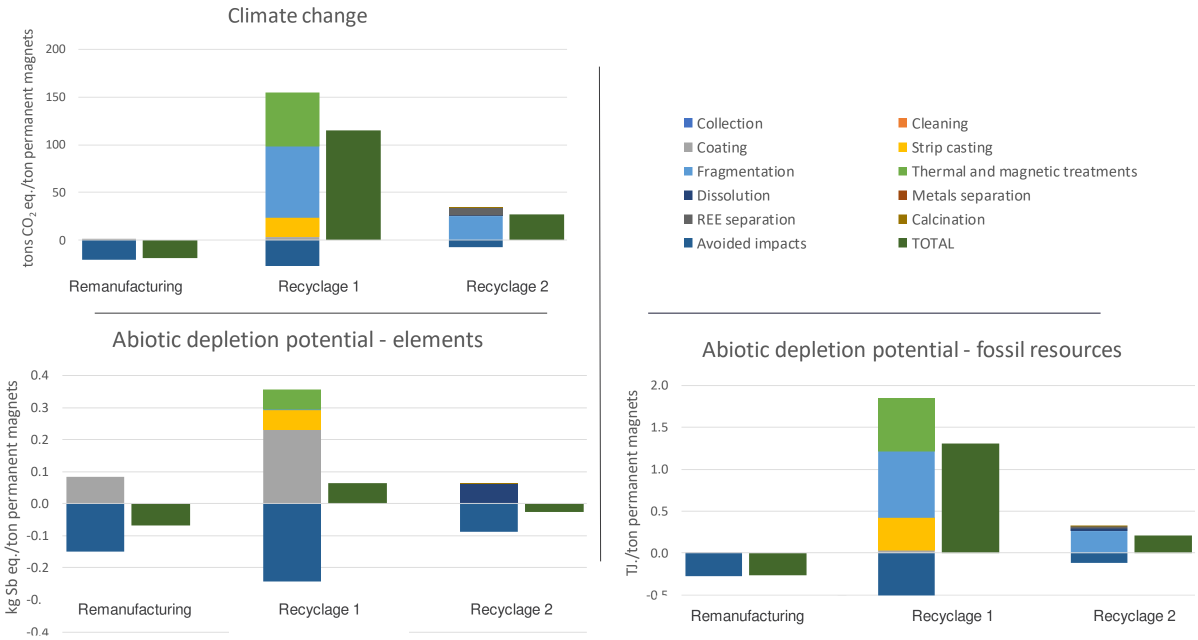


Figure 3: *LCA results of remanufacturing and recycling loops of one ton of permanent magnets (CML v3.05)*

With data estimated at industrial scale, the trend is reversed, resulting in the extraction of REE (recycling 2) having a higher carbon footprint and impact of fossil resource consumption than recycling by strip casting. However, the extraction of REE has a lower impact on the consumption of metals and minerals since it allows the recovery of materials at their highest value (in this case nickel, valued in one recycling loop but not in the other).

The “Waste” approach allows comparing the three recovery routes of magnets at their end-of-life, while the “Feedstock” approach allows comparing two approach : on the one hand the production of magnets from magnets at their end-of-life with the production of magnets from primary raw material, and on the other hand the production of REE from magnets at their end-of-life with REE from mining activities. The production of new magnets appears to have a higher impact for the three studied impact categories compared to the production of secondary magnets. On the other hand, the production of rare earth oxides from primary raw material appears preferable to the recycling of rare earths from end-of-life magnets for two impact categories out of three. The choice to use rare earth oxides from recycling or mining activity depends on the environmental issue prioritized by the sector using the REE (e.g., preservation of mineral resources or reduction of greenhouse gas emissions).

2. Case n°4: refurbishing of tires in a context of Product-Service System

2.1. DESCRIPTION OF THE SCENARIOS

The studied system has been implemented by Michelin in its commercial offer for tires called Michelin Fleet Solutions^{TM}. It is based on the principle of a Product-Service System (PSS): the sale is that of a service and not of a product. Customers opting for this offer pay for Michelin services based on the kilometers traveled rather than per tire purchased. The service includes, among others, the supply of the tires and regular inspections. Michelin is therefore responsible for the maintenance of tires and their refurbishment. The latter includes re-grooving and retreading.

The objective of this case study is to compare the environmental performance of the system implemented by Michelin for a fleet of trucks with the one of the conventional tire sales system. The functional unit is the *"set of regional range tires"* X Multi *"equipping a fleet in France of 400 trucks traveling 100,000 km per year for 5 years in a context of European production and end of life"*.

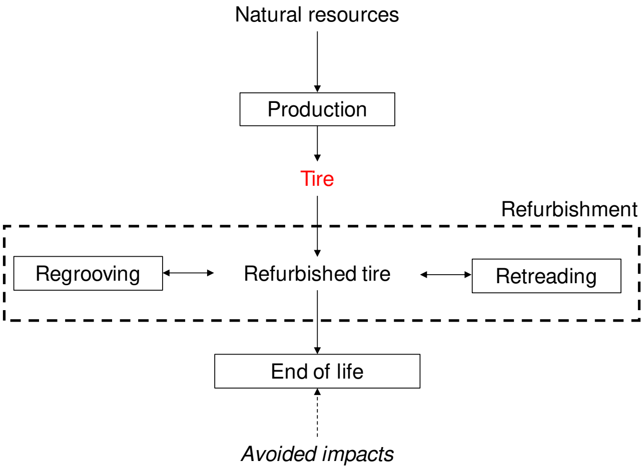


Figure 4: *Life cycle steps of the two compared scenarios (in red the reference flow linked to the functional unit)*

The life cycle stages of the tires are the same for both scenarios. Four parameters differentiate them:

- *Withdrawal height:* depth of the tire grooves at which the tires are removed from the trucks;
- *Re-grooving rate:* percentage of tires undergoing re-grooving treatment;
- *Percentage of under-inflation:* average difference between actual and recommended tire pressures during use;
- *Rate of damaged tires:* percentage of tires needing to be changed following an incident during their use.

The processes included in the system boundaries are the production of the tires, their distribution, their use, re-grooving and retreading processes and their end of life.

2.2. LIFE CYCLE INVENTORY

Inventory data was collected by Michelin for both scenarios. The parameters that differentiate them are presented in Table 1. The end-of-life mix includes material and energy recovery routes, based on Aliapur data (Aliapur 2010).

Table 1: *Parameters which differentiate the two compared systems*

Parameter	Conventional system	PSS
Withdrawal height	4 mm	4.5 mm
Re-grooving rate	50%	90%
Percentage of under-inflation	10%	0%
Rate of damaged tires	20%	15%

2.3. IMPACT ASSESSMENT AND SENSITIVITY ANALYSIS

The CML v3.05 method is applied. A sensitivity analysis is carried out on four parameters: withdrawal height (1.6 mm instead of 4.5 mm in the PSS), re-grooving rate (increased by 10% in the PSS), the rate of damaged tires and the reduction in service life due to under-inflation (both reduced by 10%).

2.4. RESULTS

The PSS has a lower environmental impact than the conventional system. The benefits are minimal for some impact categories but can reach 9% impact reduction for the categories with a preponderant contribution of raw materials for tires production (e.g., ADP elements, see Figure 5). The implemented system has the potential to be improved by reducing the withdrawal height. Today, tires are removed at an average height of 4.5 mm compared to 4 mm for the conventional system. Any effort to reduce this withdrawal height would significantly increase the benefits of the system implemented by Michelin.

This case study highlights the potential differences between the benefits estimated before the implementation of a PSS and the actual benefits, which may turn out to be lower. In fact, a withdrawal height lower than that of the conventional system was first communicated by Michelin, based on the argument of better control of the tires making it possible to "push" their use further. Actually, it has been observed that the withdrawal height is higher than the conventional system because Michelin bears the entire responsibility of any misfunction of the tires. A higher withdrawal height allows minimizing the risk of accidents that could be attributed to poor tire management.

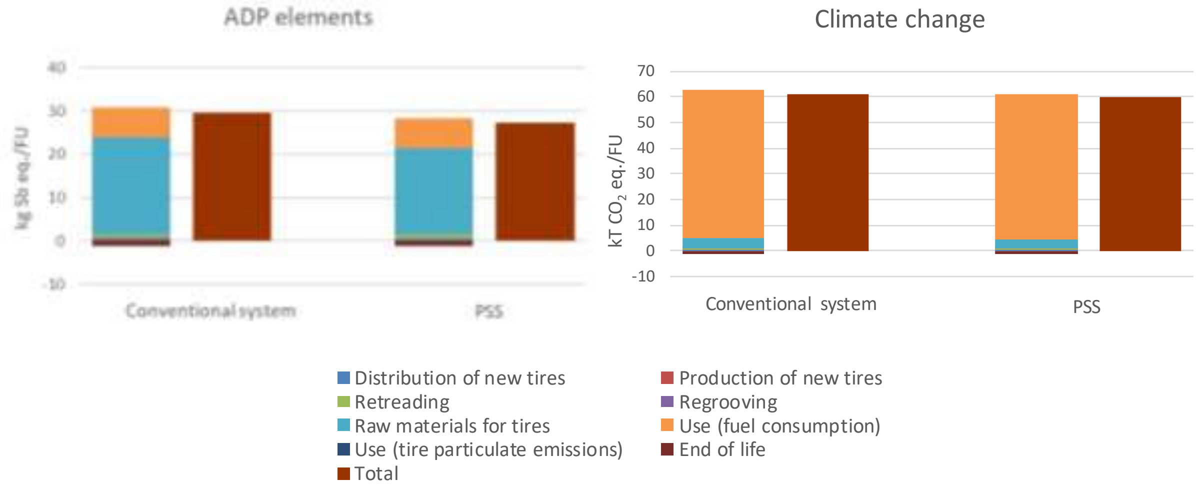


Figure 5: *Comparison of impact differences between the two systems of tire management for resource use and impact on climate change*

3. Case n°5: engine remanufacturing

3.1. DESCRIPTION OF THE SCENARIOS

The aim of this case study is to compare the environmental performance of a new engine with that of an engine remanufactured by Renault in Choisy-le-Roi. The study focuses on a type of engine called K9K. The engines come from Renault's own network and franchise garages offering a "standard exchange" service. At the remanufacturing site, the engines are disassembled and washed. During disassembly, non-compliant parts are discarded and sent for end-of-life treatment. The engines are reassembled from prepared parts sets, consisting of parts from old engines and new parts. For each remanufactured engine, approximately 1.2 used engines were required as input.

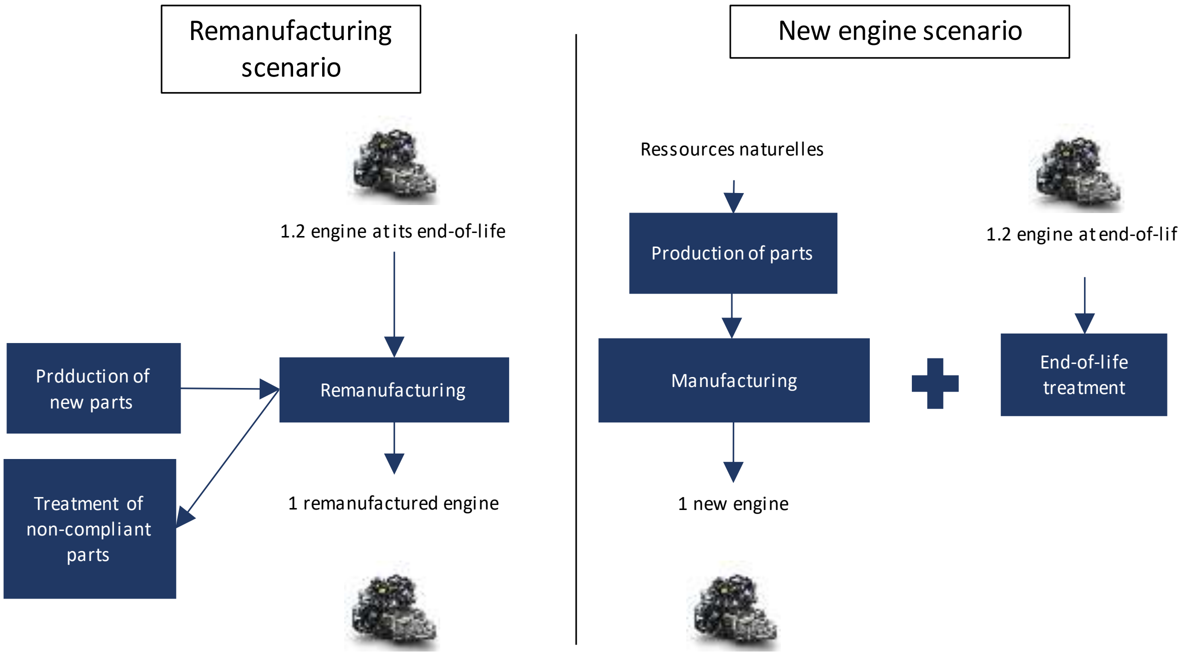


Figure 6: *Approach followed for the comparison of a new and a remanufactured engine*

A "Feedstock" approach is followed. The functional unit is *"the production of a Renault engine and the end-of-life treatment for defective engines"*.

3.2. LIFE CYCLE INVENTORY

Remanufacturing

The impact of the materials in the remanufacturing scenario corresponds to the impact of new parts necessary to produce a new engine. The bill of material of an engine communicated by Renault and the parts replacement rate were therefore used to quantify the consumption of new materials. On average, 32% of the weight of a remanufactured engine consists of reused parts. The production data for the remanufacturing site was communicated by Renault. A mass allocation is applied to allocate this data to outgoing K9K engines. All replaced parts are sent to a specific recycling process, except plastic parts, which are incinerated.

New engines

The data from the production site was communicated by Renault. The production losses are estimated based on the total amount of waste produced by the site. For parts not produced on the Renault production site (for example plastic seals, glass parts, etc.), no production losses are considered. Production losses, of which only those of aluminum, cast iron and steel are considered, are sent to recycling. The assumption is made that the end of life of an engine is the same as an end-of-life vehicle (ELV), i.e., it is sent to an ELV treatment center. Data on the quantities of materials extracted from ELVs and their destination by material are taken from Deloitte Sustainable Development et al. (2017).

3.3. IMPACT ASSESSMENT AND SENSITIVITY ANALYSIS

The impact assessment method CML v3.05 is used. In the sensitivity analysis, a "System" approach is applied, with the *“production and treatment at end-of-life of a Renault engine”* as a functional unit. In the remanufacturing scenario, the end-of-life treatment is remanufacturing, from which 0.8 remanufactured engines are produced. The remanufacturing scenario therefore produces 1.8 engines. To fulfill identical functionality, the reference scenario (“new engine”) must therefore consider the production and end-of-life management of 1.8 new engines. The sensitivity analysis also tests the variation in the number of remanufacturing loops.

3.4. RESULTS

The results show a clear advantage of remanufacturing compared to the production of new engines for all impact categories (e.g., -28 kg CO_2 eq./FU). These benefits are due to a lower consumption of raw materials but also to a better management of "precious" metals. These metals, although little reused, are sent to specific end-of-life processes after dismantling on the remanufacturing site, while they are not recovered by the conventional management routes of engines at their end of life.

The results with the "System" approach show a lower benefit from remanufacturing compared to that obtained with the "Feedstock" approach. However, they consider a realistic system in which the production of a first engine is necessary before remanufacturing. Considering the engine which enters the remanufacturing site free of environmental burden, the "Feedstock" approach does not allow a fair comparison between the two scenarios. The sensitivity analysis also showed that the difference in impact between the two scenarios obtained with the “Feedstock” approach is only achieved with the “System” approach in the ideal case of an infinite number of loops and a 100% remanufacturing efficiency. The "Feedstock" approach therefore overestimates the benefits of remanufacturing.

4. Case n°6 : industrial symbiosis

4.1. DESCRIPTION OF THE SCENARIOS

The case study is that of a waste heat exchange between a steel production site and a residential area in France. The heat demand of the residential area is based on Kachacha et al. (2019) (116 GWh/year). The production capacity of the steel site is estimated at 7.5 MT of steel per year, based on a steel production plant identified in the north of France. Waste heat can be considered as waste, therefore free of environmental impact. The functional unit is the *"production of heat delivered to a residential area in the north of France to fulfill a demand of 116 GWh/year".*

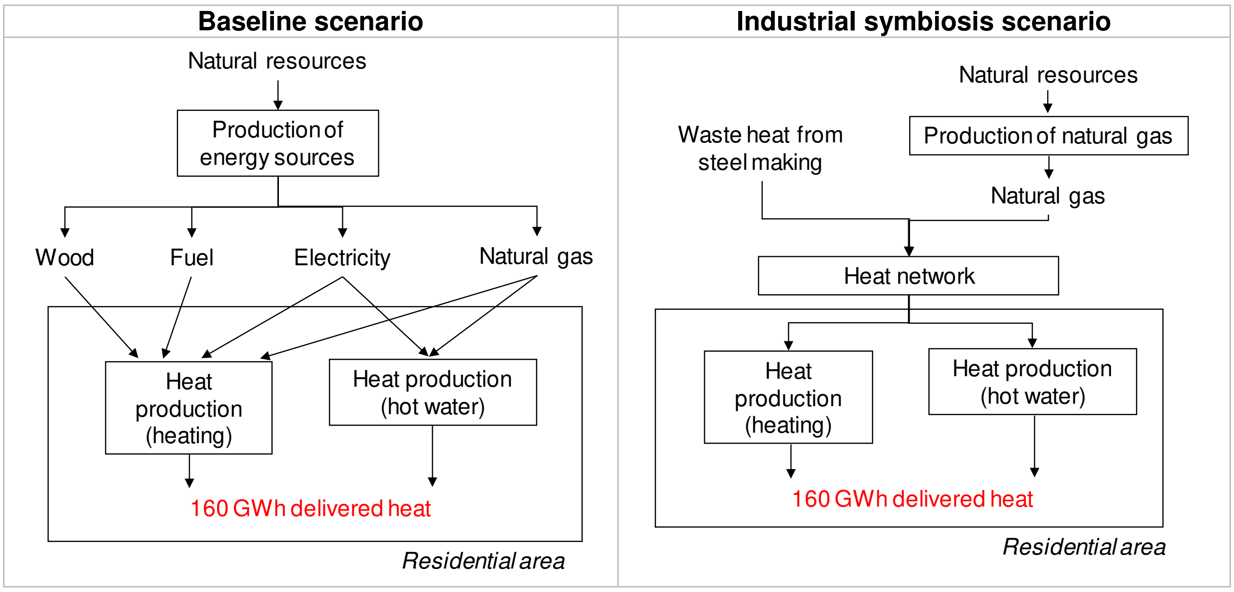


Figure 7: *Schemes representing the baseline and industrial symbiosis scenarios with the zero-burden assumption*

In the baseline scenario, the system boundaries include the production of energy sources used to produce heat as well as their conversion to heat in dwellings. Infrastructure is included in the system boundaries. In the industrial symbiosis scenario, the boundaries include the production of natural gas needed to supplement the demand and the infrastructure of the heating network (pipes and heat exchangers).

4.2. LIFE CYCLE INVENTORY

The heat production mix in the baseline scenario is taken from national statistics on energy consumption by households published by ADEME[1].

13% of the heat consumed by the iron and steel sector becomes waste heat (Papapetrou et al. (2018)). The waste heat of the steel production site is therefore estimated based on the heat consumed by the site (ecoinvent data). 3.4×10^8 MJ of waste heat is estimated to be recovered from the site by the heat network. 5% of the heat is used for the operation of the pumps and 10% is lost by dissipation (Berge et al. 2015). 3.1×10^8 MJ of waste heat can therefore be delivered to the residential area (74% of the heat demand). The heat demand is supplemented by natural gas.

The heating network infrastructure is modeled based on data supplied by EDF on the length and type of pipes as well as the number and type of heat exchangers required for a similar network. A 20-year lifespan is considered for infrastructure (Oliver-Solà et al. 2009).

4.3. IMPACT ASSESSMENT AND SENSITIVITY ANALYSIS

The impact assessment method CML v3.05 is applied. A sensitivity analysis is conducted on 3 parameters :

- The integration of the impact of heat production in the analysis. Two approaches are tested:
    - System expansion: the functional unit is defined as *the production of 7.5 MT of steel and the production of heat delivered to a residential area in the north of France to fulfill a demand of 116 GWh / year*;
    - Allocation of the impacts of the steel production site to waste heat and steel. The function related to steel production is excluded from the functional unit, which is defined as *the production of heat delivered to a residential area in the north of France to fulfill a demand of 116 GWh / year.* Two allocation factors are tested based on exergetic (4.3%) and economic allocation (0.2%).
- The heat production mix: the use of the Belgian mix is tested.

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[1] https://www.statistiques.developpement-durable.gouv.fr/consommation-denergie-par-usage-du-residentiel

- The type of dwellings considered: the hypothesis of a residential area consisting of 100% apartments or 100% houses is tested.

4.4. RESULTS

The results show a clear benefit of the industrial symbiosis scenario for all impact categories when the zero-burden approach is followed (e.g., -14.8 kg CO_2 eq./FU). The question of considering the waste heat from an industrial site as waste or as a co-product was discussed by comparing the results obtained with the zero-burden assumption, system expansion and two allocation approaches (Table 2). Only the zero-burden and system expansion approaches allow calculating the real benefits of setting up an industrial symbiosis system. By allocating part of the impact of the industrial site to waste heat, the allocation method disadvantages the industrial symbiosis scenario while resulting in a very small reduction of the impact of the industrial site (in this case a steel production site). Consequently, this approach discourages communities from setting up such a system while barely encouraging the industrial site to do so, as its impact reduction is negligible. Therefore, for a sake of reality, it is recommended to choose a zero-burden or system expansion approach rather than an allocation approach. It should be noted that this conclusion can vary from one sector to another.

***Table 2:** Difference of impacts between the two scenarios following the zero-burden assumption, system expansion and the two allocation approaches*

Approach	**Impact difference between both scenarios(1)**	
	kT CO_2 eq.	**%**
Zero-burden	-14.8	-71%
System expansion	-14.8	-1%
Exergetic allocation	+63.2	+304%
Economic allocation	-11.7	-56%

(1) Impact of industrial symbiosis scenario - Impact of the baseline scenario

The case study also showed the importance of using specific geographic data on the heat production mix. This has a major impact on the magnitude of the benefits of setting up an industrial symbiosis system.

4. Recommendations

Recommendations for the “pre-study” step

These recommendations relate to the reflection phase before carrying out the study. These recommendations can be used as a basis for arguing the need for an LCA study to compare the impacts of loops considered by an organization.

- **Recommendation 1: Do not assume (and so communicate without having conducted an evaluation) that closed loops have a lower impact than open loop**

  The literature review did not allow drawing conclusions on the preference of closed loops over open loops, nor on the preference of so-called "short" loops over "long" loops. It is therefore not an argument to be used for internal or external communication purposes.

- **Recommendation 2: For products characterized by a large contribution of the use phase (due to energy consumption), the importance of the technological evolution rate on the performance of the loops is to be used as an argument during discussions on the choice between loops**

  These products can sometimes deviate from the waste hierarchy. Technological improvements can allow new products achieving higher energy (or other) efficiency which may offset the strong impact of new materials production compared to those of reuse/preparation for reuse. This argument can justify carrying out an in-depth study of the impacts before any communication on the benefits of setting up a collection system for re-use/preparation for re-use.

- **Recommendation 3: If no resource is available to conduct a comparative LCA, the waste hierarchy can be followed**

Recommendation for goal and scope definition

- **Recommendation 4: Choose the modelling approach based on the objective of the study**

  When defining the goal and scope of the study, the choice of the approach must be justified to avoid any overestimation of the benefits from recovery loops, as illustrated with case n°5. A decision tree for choosing the approach is proposed in Figure 8.

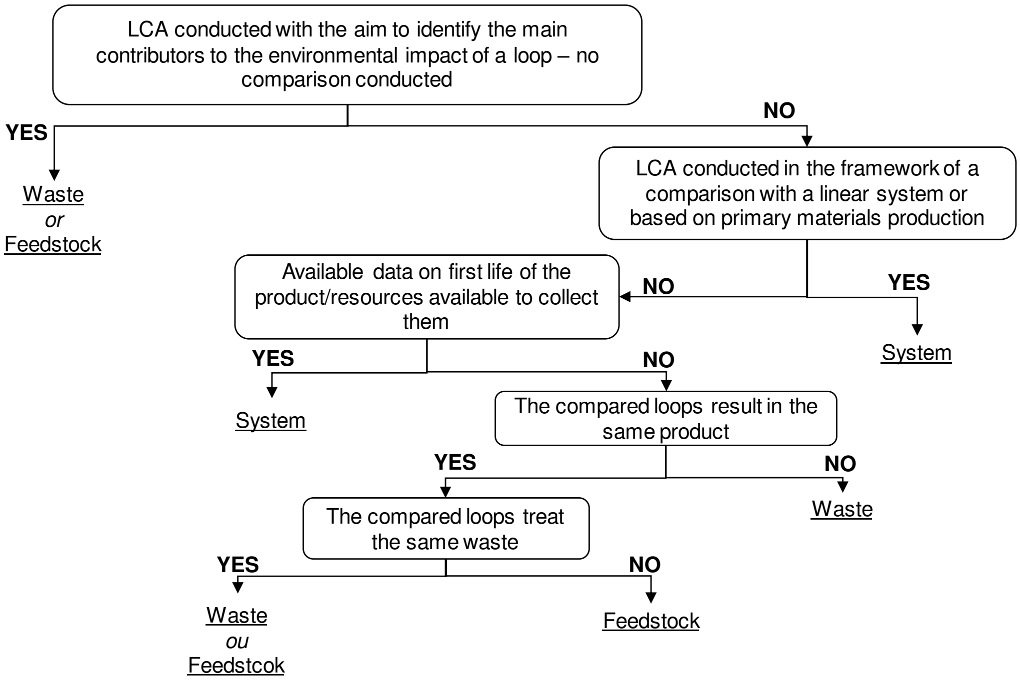

Figure 8: *Decision tree to support the choice of the approach based on the objectives of the study*

- **Recommendation 5: Include a clear scheme of methodological choices**

  The literature review revealed a difficulty in identifying the goal and scope chosen in the publications. It is therefore recommended to add a diagram showing the main methodological choices of the study in the "Goal and scope" section. This diagram should show: the functional unit (or reference flow when different), the system boundaries and the allocation choices. The purpose of this diagram is not to replace a complete diagram presenting the system boundaries but to quickly identify the perspective chosen for the comparison of the loops.

Recommendations for data inventory

- **Recommendation 6: Conduct a material flow analysis (MFA) to ensure the analysis of a coherent system**

  A material flow analysis of the recovery loops is necessary to model a coherent and understandable system. Software such as STAN can be used as representation and verification tools.

- **Recommendation 7: In prospective evaluations of Product-Service Systems (PSS), the parameters resulting in a large variability of the results should be checked with a specialized technical team**

  A retrospective analysis of the PSS implemented by Michelin on tires has shown that a key parameter supposed to optimize the system reduces its performance when the system is actually implemented (while remaining more efficient than a conventional system). A discussion with a technical team specialized for example in risk management, would help identifying the risks linked to the implementation of such a system. This is especially the case when it comes to the responsibility of the company, which is increased in the case of a PSS.

Recommendation for impact assessment

- **Recommendation 8: Choose an impact assessment method covering the largest number of resources and allowing the separation of fossil and mineral/metal resources**

  One or a combination of environmental impact assessment method(s) allowing to cover the largest number of resources must be considered in the studies. In addition, cases n°1, 2 and 3 showed that a distinction between the results for fossil resources on one hand and mineral resources on the other hand allows a better understanding of the results.

Recommendation for results interpretation

- **Recommandation 9: If the context of implementation of a loop can variate, conduct the study with the aim of identifying the contexts in which the loop is more performant than another system**

  The literature review has shown that the preference of one loop over another can vary from one context to another. When some context parameters are not yet known or may vary, it is recommended to conduct the study with the aim of identifying those in which the loop is favorable instead of searching for an answer based on fixed data. In this case, the sensitivity analysis is a central phase of the study. Based on the literature review carried out in this study, a list of key parameters to analyze is proposed.

5. References

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