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Dismantling, remanufacturing and recovering heavy vehicles in a circular economy

Technico-economic and organisational lessons learnt from an industrial pilot study

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Abstract:

To date, a limited number of in-depth case studies addressing the end-of-life management of heavy vehicles has been reported in the scientific literature. An action research approach is conducted in collaboration with an emerging international remanufacturing center of heavy handling machines to bring a contribution to this gap in a circular economy perspective. This industrial pilot study considers the entire end-of-life management of a whole heavy vehicle, from the dismantling to the recovery of used parts, through remanufacturing. It illustrates as such the multiple dimensions to consider when closing-the-loop on heavy vehicles, namely: technical and organisational knowledge (e.g., infrastructures, tooling, dismantling process and remanufacturing feasibility), as well as economic considerations (e.g., solutions to optimize the value recovered according to market needs, through the identification of potential recovery channels). To do so, a multi-scale modelling is proposed, taking into account: (i) the condition of the used vehicle and residual values of key components, (ii) the dismantling process and capabilities, (iii) the possible end-of-life options and associated market. A first dismantling operation on a worn-out 8-ton forklift truck is performed and closely analyzed to identify hotspots and areas for improvement. Based on that and taking inspiration from the best practices of the automotive recycling sector, a new dismantling process is designed including improvement in terms of organisation, resources used, disassembly time, and comfort for the operator. This newly proposed process is then tested and validated through a second dismantling experimentation on a similar forklift truck. Moreover, a practical spreadsheet, to be used by the industrialist, is proposed and applied as a decision-making support tool to compare and select the most appropriate end-of-life pathways for recovered components according to the economic aspects of each circular option, among reuse, remanufacturing and material recovery. Eventually, lessons learnt from this industrial case study open up on broader implications and challenges (e.g., the applicability, generalization and scaling-up of commendable practices from one industrial sector to another) to achieve a more advanced circular economy in the heavy vehicle industry.

Key words:

Heavy vehicles, circular economy, dismantling process, remanufacturing, economic recovery, industrial case study.

Highlights:

- An industrial pilot study is conducted with an emerging remanufacturing center of heavy vehicles.
 - A new disassembly process is proposed, experimented and validated on a second dismantling operation.
 - Improvements in terms of lead time, resources used and comfort for the operator are assessed.
 - An economic analysis of recovery potentials is made based on a multi-scale model.
 - Recommendations to advance circular economy practices in the heavy vehicle industry are given.
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1. INTRODUCTION

1.1. MOTIVATION: CLOSING-THE-LOOP ON THE HEAVY VEHICLE INDUSTRY

Remanufacturing is the closed-loop industrial process of restoring used products to like new condition by a certain process of cleaning, disassembling, inspection and assembling. It is an efficient circular strategy in waste management and sustainable manufacturing to close-the-loop (Pigosso et al. 2010) on industrial components, by extending their useful lives rather than being landfilled or recycled, and by recapturing as such their added value. Indeed, the Remanufacturing Industries Council (2018) inventoried the potential beneficial impacts of remanufacturing practices, including: cost savings for the manufacturers and lower prices for the customers, higher profit margin, better customer relationships availability with a shorter lead time, associated services (e.g., leasing, take-back, upgrading), reduced raw materials consumption, reduced energy consumption, reduction of CO₂ emissions, reduction of materials sent to landfill, creation of local and skilled jobs, new manufacturing techniques.

Yet, exploiting the potential profitability of a remanufacturing activity is not straightforward and depends on several factors, such as: the collection process and reverse logistic, the uncertain condition of a returned product, the additional cost and necessary resources. In fact, Casper and Sundin (2018) discussed today's challenge in the automotive remanufacturing, from the collection of used vehicles to the disassembly and recovery of key parts. The main fields of challenges identified are: the important need for a continuing qualification of staff and engineers, an efficient core management, the consideration of pricing models and the competence to handle the growing variety and complexity of core parts in terms of quality and location. Sandvall (2006) demonstrated that once a remanufacturing activity is set up on appropriate circumstances, costs and machine downtime could decrease, and also reminded that it is not systematically the option to follow, stating that sometimes other end-of-life alternatives are better. On this basis, implementing an efficient and effective remanufacturing activity in the heavy vehicle industry needs to be supported by suitable expertise, methods and tools.

1.2. INDUSTRIAL CONTEXT

Presently, the end-of-life management of heavy vehicles is still a marginal activity, not submitted to end-of-life regulation, which leads to the leakage of high added value components and precious materials (Saidani et al. 2018a). Moreover, circular economy (CE) and sustainability considerations applied to the heavy vehicle industry are fresh research themes (Xiao et al. 2018). Contrary to light vehicles - i.e., passenger cars which are subject to an end-of-life regulation (Directive 2000/53/EC) with mandatory recycling and recovery rates - the end-of-life management of heavy vehicles is a barely addressed issue in scientific literature. Meanwhile, when political actions are neither proactive nor supportive, closing-the-loop has to be motivated by other considerations, such as economic ones (Accenture, 2016). In fact, the absence of end-of-life regulation in the heavy vehicle industry makes particularly relevant and challenging to seek improvement potential, suitable circular strategies, and key actions levers to close-the-loop on heavy-duty and off-road (HDOR) vehicles and associated key components. Based on the significant quantity of end-of-life vehicles and their remaining economic value (ADEME, 2006), there is a real end-of-life economy to create in a CE perspective (CETIM, 2014), by optimizing the collection, dismantling and recovery of such vehicles, and by putting back on the markets the materials, components and vehicles resulting from the circular practices and loops, namely: maintenance, reuse, remanufacturing and recycling. Nevertheless, no economic model has been validated yet by the actors in that sector. In fact, at present, this industry is facing a lack of infrastructures, methods and support to do so. When existing, dismantling processes are poorly designed and are often incorrectly dimensioned. In addition, the complexity of this industrial sector, plus its considerable environmental and economic impact, makes it particularly relevant from a research perspective for figuring out how to implement circular practices. Against this background, original equipment manufacturers (OEMs) from the heavy vehicle industry are increasingly recognizing the potential of CE models to increase the value of their products and materials and to mitigate the risks associated with volatile materials prices and supply.

The Manitou Group is a large equipment manufacturer, designing, developing and manufacturing mainly handling, lifting and earthmoving machineries, such as forklift trucks. Even if the heavy vehicle industry is presently not subject to the ELV Directive 2000/53/EC, Manitou is increasingly concerned about the end-of-life fate of its heavy machineries, based on the following reasons: growing customer demand related to the

maintenance, take-back or end-of-life recovery of their equipments, potential economic benefits by exploiting this market and associated value bucket, anticipation of possible upcoming regulations on the obligation to offer second-hand parts (like in the automotive industry in the EU), business competition with independent remanufacturer, and a CSR policy more and more interested in applying CE principles. Against this background, Manitou has recently launched its “Reman Parts Program” to expand its products portfolio by offering the possibility to buy second-hand and remanufactured components. To further develop this offer and feed its stock of parts that are potentially recoverable, a subsidiary entity, the Manitou International Remanufacturing Center, has been created in 2013. Even if this fresh entity interacts with other departments of Manitou, such as the engineering design, or the parts and services departments, the remanufacturing center can be viewed as a SME (small and medium enterprise), composed of two technical managers, one accounting officer, one sale manager, one purchasing manager, and four technicians.

As such, this remanufacturing center is currently looking to extend its remanufacturing offer and to enhance their current practices, in order to achieve a sound and profitable end-of-life management of the collected machineries. Particularly, after some preliminary discussions and a rapid industrial diagnosis, many areas of improvement have been identified, from the dismantling process to the selection of best end-of-life options for the recovered parts, through the remanufacturing of key components. In this way, we found relevant to study to what extent best practices analyzed in essay #1 could be transposed in their industrial practices. Additionally, to fully exploit this case study and provide relevant solutions that match with industrial reality, a complementary literature survey and further ground investigations have been performed, resulting in the proposition of a multi-scale model to select the most appropriate end-of-life options considering (i) the condition of the used machinery, (ii) the capabilities of the dismantling and remanufacturing activities, (iii) the recovery channels available. Last but not least, a practical datasheet and its associated spreadsheet have been designed to assist the industrialist all along the end-of-life operations.

1.3. OBJECTIVES AND EXPECTED RESEARCH CONTRIBUTIONS

To date, a limited number of in-depth case studies addressing the end-of-life management of heavy vehicles have been reported in the scientific literature (Xiao et al., 2018). Indeed, from a research perspective, the end-of-life management of such heavy vehicles has been less studied than to the end-of-life management of light-duty vehicles (i.e., passenger cars). In addition, the complexity of this industrial sector, plus its considerable environmental and economic impact (Saidani et al., 2018a), make it particularly relevant for figuring out how to implement circular practices. Through this industrial pilot study, the objectives are not only to bring a contribution to fill this gap but also to provide the original equipment (re)manufacturer with insights and practical solutions in the following areas:

- Technical and organizational: to optimize their dismantling process (in terms of resources used, tooling, working conditions, disassembly time);
- Economic: to assess, enhance and monitor the profitability of their remanufacturing activities (i.e., to know how to extract more value out of their machines and key components after use);

A complementary objective is to provide insights on how to implement the best practices and methodologies from an industrial sector (automotive industry) to another one (heavy vehicle industry), as well to discuss the replicability and generalization of the proposed approach and models in other industrial environments to close-the-loop on heavy vehicles. In addition to the issues related to the characterization of the used heavy vehicle and the modeling of the dismantling process, the scientific challenges are also to develop an integrated and systemic modeling of the possible recovery channels, so as to explore and compare the end-of-life alternatives before deciding on the most appropriate one(s) from a technico-economic perspective.

Last but not least, a key contribution of this study lies in finding out, through the industrial pilot study and close interaction with industrialists of the remanufacturing center, a suitable way to integrate academic and conceptual CE framework to a more practical one for real and sustainable industrial use. In fact, research on circular economy must be conducted with the purpose to deliver practical and easy-to-use toolkits in order to facilitate a sustainable industrial development (Bonet et al., 2014). In this line, this study particularly provides the industrialist with readable and easy-to-use versions of the models developed through (i) a template

document to collect the data, and (ii) a spreadsheet, as a decision support tool to select the best end-of-life options.

With this background, the present study aims to provide new insights on how to identify and apply improvement potentials in the end-of-life management of heavy vehicles, from the dismantling to the economic recovery of such worn-out heavy vehicles, through remanufacturing operations. Figure 1 gives a synthetic overview of the content of this research work conducted in collaboration with a remanufacturing center of heavy vehicles.

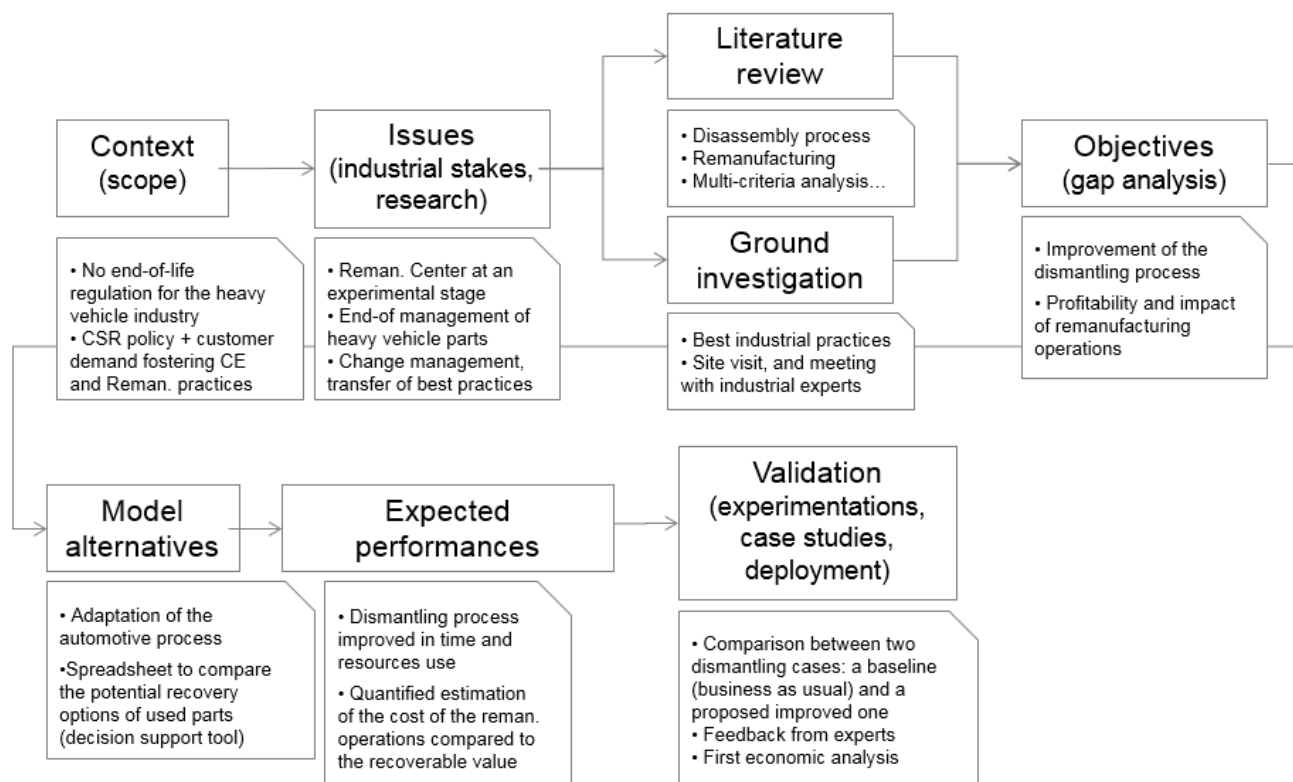


Figure 1 – Synoptic view of the industrial pilot study conducted with a remanufacturing center of heavy vehicles

2. MATERIALS AND METHODS

2.1. COLLABORATIVE ACTION RESEARCH APPROACH

The main research approach used in this study is an action research pilot study conducted in collaboration with an industrial actor of the end-of-life management of heavy vehicles. In an action research approach, the researcher moves from the role of neutral observer to a more active participatory role whilst retaining academic rigor (Gustavsen, 2008; McManners, 2015; Bocken et al. 2018). Moreover, case studies are detailed empirical investigations into a complex entity that are valuable for making a theoretical contribution (Rigger et al., 2009). For instance, Rigger et al. (2009) demonstrate that conducting case studies can enhance practical knowledge in strategy and management research. Interestingly, action research case studies have shown their relevance to push forward both the research and industrial practices in pressing areas such as sustainability challenges (Yin, 2013; Bocken et al. 2018). Particularly, a pilot experiment is a small-scale preliminary study conducted in order to evaluate the feasibility (e.g., in terms of time, cost, resources) of an emerging activity prior to consider a full-scale implementation (Eldridge et al. 2016).

The findings presented hereafter are the result of a one-year collaborative research project part with Manitou Reman, as illustrated through the timeline of the project in Figure 2. The detail of the main steps, activities and outcomes related to this industrial pilot study are described in Table 1. Particularly, the first in-depth analysis of a dismantling operation has allowed to highlight the hotspots and areas of improvement.

Feedbacks from the technician and the reman. manager, as well as from the design department, have been actively sought to perform a workshop aiming at generating improvement solutions for the dismantling operations. As a result, a proposed dismantling process has been tested and validated through a second dismantling operation. In parallel, key information has been collected following the developed data template, and a spreadsheet has been designed to organize and compile these data so as to guide the reman. manager in selecting the best end-of-life options for the recovered components.

Notably, this action research case study combines inputs from scientific literature review with best practices from field investigations (sub-section 2.2) to propose a multi-scale model and associated tools to manage the end-of-life activities in practice (sub-section 2.3), in order to achieve the aforementioned objectives, and thereby to meet the industrial needs (section 3).

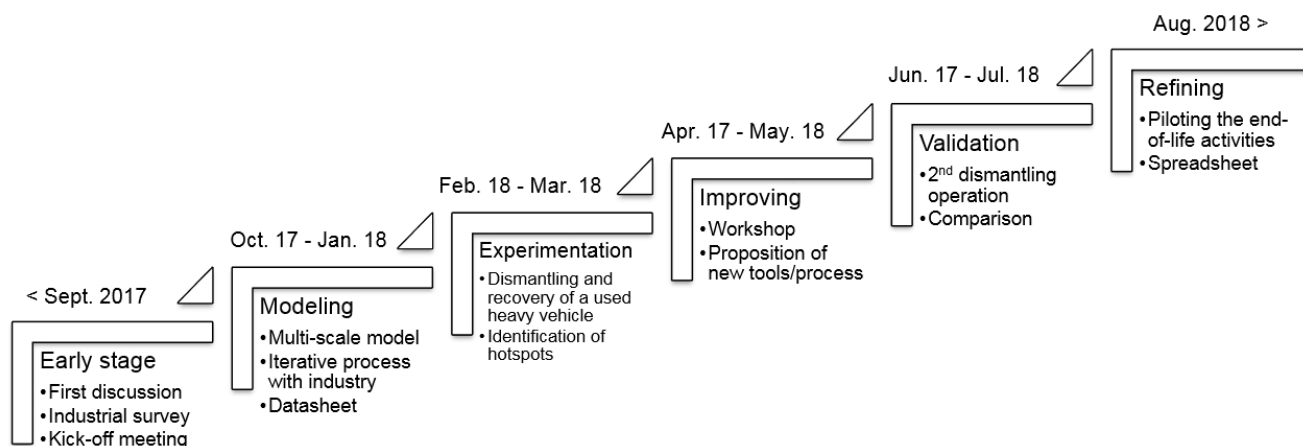


Figure 2 – Stepwise process of the industrial pilot study conducted with Manitou Reman

Table 1 – Detail of the key steps, activities and deliverables of the industrial pilot study

| Steps | Inputs / Activities | Outputs / Deliverables |
|-----------------|--|---|
| Early stage | Several meetings (first presentation, industrial survey, identification of shared interest, feasibility of such pilot study, project kick-off). | Definition of objectives, expected deliverables, required data and available resources (end-of-life machinery, technician, intern recruitment). |
| Modeling | Inspiration from literature review and best practices from the automotive industry. Data preparation and first collection (iterative process with reman. manager). | Multi-scale model with multi-dimension data. Practical and integrated data template (see Appendix A). |
| Experimentation | Observation, photos, and videos, of the dismantling operations. Industrial visit of the remanufacturing center. Further round of data collection and analysis. | Organized timeline of the dismantling process. Identification of hotspots (problems and pains), and areas of improvement in the disassembly operations. |
| Improving | Post-treatment analysis of the dismantling operations. Workshop with inputs from technician, reman. manager, design department, parts and services department, and inspiration from the well-defined and streamlined dismantling process in the automotive industry. | Proposition of new tools to facilitate and accelerate several disassembly operations. Proposition of a newly time-efficient and well-organized dismantling process. |
| Validation | 2 nd dismantling and recovery of an end-of-life heavy vehicle. Feedback from the technician and reman. manager. | Spreadsheet for the dismantling operations. |

| | | |
|-----------------------|--|--|
| | | First economic analysis (cost and benefits of the reman. activity) with data provided by several departments of the OEM. |
| Interpreting Refining | Further organizational, technical, economic and environmental analyses. Complementary economic and market demand data given from the sales department, and from the parts and services department. | Spreadsheet to calculate the profitability of reman. activities comparing possible end-of-life options for the recovered components. Initiation of a dismantling manual. Identification of further and promising challenges for a full-scale implementation. |

2.2. LITERATURE REVIEW AND FIELD INVESTIGATIONS

This sub-section presents the specific literature and the industrial practices, as depicted in Figure 3, that have been used as inspirational sources to improve the dismantling process, or are expected to be used to further improve the developed spreadsheet, as well as to provide insights in the design of future generations of heavy vehicles (e.g., considering design for remanufacturing, for end-of-life-recovery or for circular economy approaches).

As studies related to the end-of-life management of heavy vehicles are scarce in the scientific literature published, it is particularly relevant to question the transfer of best practices from the automotive recycling industry, as well as to further investigate on the industrial ground to look at emerging circular practices implemented in the heavy vehicle industry, and to exchange with other industrialists in this field who are interested or are starting to conduct similar industrial pilot studies. This sub-section synthesizes the literature survey and findings from the industrial ground, so as to select the approach or to propose a mix of approaches that seems relevant to fill the need of this pilot study.

Literature review State of the art



- Disassembly methods and tools
- Remanufacturing process and guidelines
- Model-based engineering approaches
- Multi-criteria analysis
- Economic and environmental indicators
- Circular business model

Field investigations Industrial practices



- CIDER Engineering: expertise center in the EoL management of heavy vehicles
- INDRA Automobile Recycling: adapted and advanced solutions to ELVs
- Caterpillar, Volvo CE, Fenwick-Linde: examples of circular EoL practices
- Manitou Reman. Center: iterative process to properly define and feed the template

Figure 3 – Themes and key words guiding the literature review and field investigations

2.2.1. Foundational research studies and positioning

Few studies addressing the end-of-life management of heavy vehicles in practice have been reported in the academic literature, compared to the numerous cases in the automotive (light-duty vehicles) industry (Saavedra et al., 2013; Saidani et al., 2018a). Saidani et al. (2018b) analyzed and compared of best CE practices in both automotive and heavy vehicle industries in the EU and in the U.S. They particularly highlighted and discussed the remaining challenges the heavy vehicle industry has to address to shift towards more CE practices and the need for conducting and reporting industrial case studies in this sector, which can help developing innovative processes and new control of procedures the end-of management of such

vehicles. In a nutshell, whereas the end-of-life (EoL) processing of the automotive sector is increasingly well-organized and fully formalized in the EU, the EoL management of heavy vehicles is more disparate, less developed and poorly controlled.

On this basis, Saidani et al. (2018a) argue the HDOR vehicle sector can learn from the automotive sector in the following areas of best circular practices: (i) well-established dismantling and systematic recycling procedures in authorized treatment facilities, motivated and propelled by the ELV directive 2000/53/EC; (ii) involvement of engineering expertise centers (e.g., INDRA operating in France) within the EoL value chain to help closing the loops by providing state-of-the-art tools, methods and software platforms; and (iii) transparent collaboration networks between automotive manufacturers, EoL treatment facilities and intermediary third parties from the EoL value chain.

Xiao et al. (2018) addressed the issue of the environmental performance of remanufactured loading machine through an industrial case study. They made an environmental comparison between original manufacturing and remanufacturing loading machines in China, using a standard life cycle assessment approach. While Xiao et al. (2018) have demonstrated environmental benefits enabled by remanufacturing activities in a well-developed and well-established remanufacturing company and its associated centers in China, in the present article, complementary insights are provided by focusing on the technico-economic and organizational aspects of a newly developed remanufacturing center in France.

2.2.2. Complementary insights from industrial actors in the automotive and heavy vehicle industries

First, a focus is made on the know-how of French industrial centers having a hands-on expertise in the end-of-life management of light-duty vehicles (INDRA Re-source engineering solutions) and in the dismantling process of heavy vehicles (CIDER Engineering). Then, a recent insightful dismantling operation on two heavy military supervised by Nexter Systems is shortly mentioned (due to confidentiality reasons, not to disclose sensitive information). Finally, examples of best remanufacturing practices in the heavy-duty and off-road vehicle industry reported by the European Manufacturing Network (ERN) are analyzed.

INDRA Re-source engineering solutions has developed engineering and software solutions to ease the disassembly of end-of-life vehicles (ELV) and manage the economic recovery of second-hand parts or used materials. In fact, all of INDRA's authorized ELV centers benefit from the same software solution to support them in their work related to the end-of-life management and recovery of used vehicles, including: a computer-based tool for the administrative management of vehicles (V2), and a software (6PO) to facilitate the dismantling and to manage the stock demand, levels and sales. As such, 6PO enables the technical identification of reusable parts intended for resale. According to INDRA, operating this network enables recycling companies to benchmark and share good practice techniques, in order to meet government targets and to increase their visibility.

CIDER Engineering is an engineering and expert center dedicated to dismantle, recycle and remanufacture heavy equipments and vehicles, with the purpose of helping companies, producers and manufactures in the end-of-life management of their heavy vehicles. CIDER Engineering entails a documentation center dedicated to the reuse, recovery, recycling and dismantling process technologies. CIDER Engineering used to have a workshop equipped with industrial means to study and carry out the dismantling of any type of heavy equipment. Their industrial tools enable: to study the means, methods and processes suitable for the treatment of end-of-life vehicles; to increase reuse, recycling and recovery rates; to propose innovative and ergonomic dismantling tools; to prepare dismantling industrialization. Notably, the discussions with the manager of Cider Engineering have contributed to have a first comprehensive and detailed view of the issues related to the end-of-life management, and then to make an inventory of all the data that must be considered in the economic analysis of end-of-life options, considering (i) the conditions of the used heavy vehicles, (ii) the dismantling process, (iii) the potential recovery channels.

Nexter Systems, a manufacturer of military heavy vehicles has recently conducted a pilot study on the dismantling of their end-of-life equipments. Through the dismantling of two military vehicles, the goals were to identify the locks and to assess the performance of the disassembly operations (costs, technical feasibility, recycling rates, etc.) in order to propose areas for improvement in design. A comparison has been made between the theoretical and effective recyclability of the military vehicles, using the ELV Directive (2000/53/EC)

as a reference. All in all, the complete dismantling, including disassembly of the vehicle, disassembly of the components, sorting, storage and denaturation (specific to the military industry), requested 3 operators and lasted 440 hours. Finally, an economic analysis has been conducted comparing the costs of such operations with the potential economic recovery of the remaining parts and materials.

The European Remanufacturing Network, through its remanufacturing processes toolkit (ERN, 2016), provides state-of-the-art knowledge and experience as well as best practices of various successful remanufacturing companies. It includes notably two examples of companies that manufacture forklift trucks and have implemented successfully a remanufacturing activity. On the one hand, Fenwick-Linde has developed a collaborative network with channels of collection, sorting, revalorization. 98% of the components of their end-of-life forklift trucks could be recovered or recycled, and annually 83% of the 2,700 tons of end-of-life waste (oil, tires, batteries, etc.) are recovered. The company has also a standardized remanufacturing process, as it follows: (i) control machine conditions; (ii) check components, and replacement if needed; (iii) repaint; and (iv) quality control. On the other hand, Toyota Material Handling Sweden indicates 90% of the used forklift comes from rental agreements that run from one month to 10 years (the rest is bought from the market), and their remanufactured forklift trucks (that are given with a warranty of 3 months or 6 months) are respectively sold at a price of 60% or 80% of newly manufactured forklift trucks (that usually come with a warranty of 12 months). The 5-step remanufacturing process implemented is the following: (i) inspection at the gate to determine the age, wornness and ability of the used forklift truck to be sold to a new customer; (ii) cleaning the forklift truck in an environmentally controlled manner; (iii) repairing parts that needs to be repaired, changing wear and tear parts; (iv) repainting to meet the new customer demands; and (v) testing the remanufactured forklift truck to ensure it meets the new customer requirements.

2.2.3. Economic and environmental analysis of end-of-life strategies

Through a case study with Volvo Construction Equipment, aiming at implementing and expanding the remanufacturing activities in Russia, Sandvall (2006) questioned “what variables are necessary to define why and how Reman can be a possible alternative to buy a new product or simply repair an existing one, and when alternatives are a better option?” For the implementation of a remanufacturing activity, this study highlighted several key variables which are: the level of regulations, range of components, mass, age of machines, usage of machines, cultural acceptance of reman, customer education of reman, costs of exporting/importing used components and reman components, costs of transportation of used components and reman components, costs of adding reman to an existing production plant, costs of setting up a production plant with reman, market potential, market stability, market strategic importance.

Moreover, an end-of-life option decision problem requires the considerations of the revenues and costs (economic and/or environmental) of each alternative available for a component. Lee et al. (2001) used an objective function to determine the optimal end-of-life options considering simultaneously the end-of-life cost and the environmental impact. To compute the end-of-life economic value of components, the following costs and potential benefits are taking into account: the reuse value, remanufacturing value, recycle value, incinerate value, landfill cost, special handling cost, collection cost and processing cost. Lee et al. (2010) developed an end-of-life decision model for determining the economic levels of remanufacturing and disassembly under environmental regulations. Lee et al. (2014) proposed a product end-of-life index that enables designers to make informed decision on design alternatives for an optimal product performance at the end-of-life stage.

Japke (2009) developed a methodology to assess the economic benefits of a remanufacturing activity, applying the following steps: mapping the process of remanufacturing; reporting the cost drivers associated with each stage of the process; computing the different types of costs that are involved in the process. The cost elements include: the transportation cost, cleaning cost, categorizing cost, disassembly cost, inspection cost, remanufacturing cost, assembly cost. The cost drivers encompass: the number of parts, the reverse logistic distance, part weight, part size and material type. To facilitate its computation, the generic cost estimation framework has been developed in Microsoft Excel, it includes input/output sheet, cost calculation sheet, and assumption and ground rules sheet (Japke, 2009). To Kwak and Kim (2013), the profitability of remanufacturing is a function of {original product design, quality and quantity of EoL products, cost of remanufacturing operations, feasibility, technical and operational issues, market demand for remanufactured products, reuse or upgrade question}. Through a case study considering a manufacturer that produces new products and also remanufactured versions of the new products that become available at the end of their life

cycle, Kwak and Kim (2015) proposed a decision-support model to maximize the total life-cycle profit. The proposed model searches for an optimal product design (design specifications and the selling price) for the new and remanufactured products. It optimizes both the initial design and design upgrades at the end-of-life stage and also provides corresponding production strategies, including production quantities and take-back rate. The model, available on a spreadsheet with the use of a solver, has been extended to a multi-objective model that maximizes both economic profit and environmental-impact saving, under the green profit zone, a pareto-like surface (Kwak and Kim, 2017).

Luglietti et al. (2014) developed a decision support tool to evaluate the environmental and economic implications of different end-of-life strategies, and applied it to an end-of-life automotive engine. In particular, three alternatives end-of-life options are compared: remanufacturing, reuse and recycling (material recovery). The results are shown in a bidimensional graph (eco-efficiency diagram) displaying the three alternatives with their economic revenue and environmental gain. The environmental impact assessment (in CO₂ eq. emissions) of the three end-of-life alternatives considers: the treatment process for each option, the recycling process for the material recovery option, the avoided manufacturing for the reuse and remanufacturing options, and the avoided raw materials extraction for each option. The revenue associated to material recovery option corresponds to the revenue from selling materials (steel, cast iron and aluminum). The revenue associated to the reuse and remanufacturing options corresponds to the selling of the second-hand or newly refurbished engine. The operation costs for all options include energy consumption and operation costs. Igarashi (2016) used a model of multi-criteria optimization for lower disassembly cost, higher recycling and CO₂ saving rates by an environmental and economic parts selection, and subsequent disassembly line balancing. The results are highlighted on a pareto-optimal frontier through a 3-dimension chart with the following axes: recycling cost, recycling rate, CO₂ saving rates. Ma and Kremer (2015) proposed a fuzzy logic-based approach to determine product component end-of-life option, considering trade-offs between the three dimensions of sustainability: the residual value for the economic pillar; the land use and eco-indicator for the environmental pillar; the human toxic potential and job creation for the social pillar.

Van Loon and Van Wassenhove (2017) developed a tool that manufacturers can use to assess whether remanufacturing is economic and environmentally attractive compared to the production of new components, via the use of several variables describing the costs of acquiring used products, the remanufacturing operations and the sales activities. The decision variables are the twofold: the number of used products, and the number of reused components. The parameters considered are: the number of refurbished components, number of recycled components, number of new components, demand for remanufactured products, fraction of reusable components present in the used product, fraction of non-reusable components, purchase price of one used component, cost of acquisition, cost to disassemble one used product, cost to refurbish one component, cost to recycle one component, cost to buy one new component, cost of additional small parts per remanufactured product, cost of assembly, cost of distribution, and the environmental impact of aforementioned activities (i.e., collection, disassembly, refurbishing, assembly, transportation, recycling). Based on their analysis with a supplier in the automotive industry, Van Loon and Van Wassenhove (2017) found that used core prices and remanufacturing yield rates have a large impact while an optimized design for remanufacturing can only marginally improve the situation.

2.2.4. Design for disassembly, remanufacturing and end-of-life recovery

In addition, eco-design or circular design approaches such as design for disassembly, for remanufacturing and for end-of-life recovery can be insightful both to further study what variables are important to consider in our analysis and to be able to provide relevant feedback to the design department after the possible identification of hotspots during the disassembly of the used heavy vehicles.

Pigosso et al. (2010) presented five eco-design methods focused on the integration of end-of-life strategies, with a special attention to remanufacturing. Hatcher et al. (2011) provided a comprehensive review as well (analyzing the format, style, key purpose, design stage, advantages, disadvantages, and use in industry) of several design for remanufacturing methods and tools developed by academics, including for instance, the REPRO² tool or the RemPro matrix which are detailed below. One striking observation made by Hatcher et al. (2011) is that these tools are barely used in industry. On this basis, Hatcher et al. (2011) made some key recommendations for future research, including: the need for greater exploration into the organizational factors affecting the integration of design for remanufacturing approaches into the design process, the need to study or test different products and case companies, and the need to investigate the value of design for

remanufacturing, both from a designer perspective and a remanufacturer perspective. For instance, Ismail (2016) developed a framework to guide designers toward sustainable remanufacturing, fostering the industrial uptake of the existing academic methods and tools related to remanufacturing.

The RemPro matrix (Lindkvist and Sundin, 2016) shows the relationship between the essential product properties (ease of identification, verification, access, handling, separation, securing, alignment, stacking) and the generic remanufacturing process steps (inspection, cleaning, disassembly, storage, reprocess, reassembly, testing), indicating to the designer which product property facilitates each remanufacturing process step. The REPRO² (REmanufacturing with the aid of PROduct PROfiles tool) (Lopez-Ontiveros, 2004) is a design tool which aims to assist designers in creating products which are easier to remanufacture. By studying the profile of 28 products already remanufactured with success, core variables which are essential for the success of remanufacturing operations have been identified, including: the ratio between the remanufactured product price and the new product price, the ratio between the buy-back cost and the new product price, the ratio between the remanufacturing cost and the new product price, the ratio between the energy required for remanufacturing and the energy for new production, the ratio between the mass of recovered components and the mass of the product.

2.3. PROPOSED METHOD AND SUPPORTING TOOLS

2.3.1. Overall modeling approach

The objective is to provide the industrialist (e.g., reman. manager) with a readable methodology and practical tools to determine systematically the most appropriate end-of-life alternative(s) for the used heavy vehicles collected and recovered components after the dismantling operations, regarding the conditions of the worn-out vehicles and associated components, the market demand and the potential recovery channels.

To do so, the global model must integrate different micro-models, as illustrated in Figure 4, characterizing at complementary scales: (i) the conditions of used heavy vehicles and associated components; (ii) the capabilities of the reman. center and related performance of the dismantling process; and (iii) the possible end-of-life options according to the existing channels for materials recovery and regarding the market demand for used or remanufactured spare parts. As such, the proposed approach supports decision-making at three key moments for the industrialist in the process of remanufacturing an heavy vehicle: (i) when taking-back the used or end-of-life heavy vehicle, to properly evaluate and negotiate its remaining value according to elements described in Figure 4; (ii) before and during the dismantling process to figure out the level of detail of the dismantling operations taking into account the wear and tear of the equipment, the capabilities of the reman. center and the market demand for second-hand parts and materials; (iii) once the recovery of the equipment is done to select best circular economy loops or end-of-life pathways according to the elements listed in Figure 4.

In this pilot study, the remanufacturing, repairing and resale of the entire heavy vehicle (i.e., the heavy vehicle as a functional whole) is not considered (according to preliminary discussions with the reman. manager, the two used heavy vehicles collected to conduct the two dismantling experimentation can only be valued through the reuse, remanufacturing of spare parts or by the recycling of materials). As such, the end-of-life options considered for each component are the following: reuse as it is to feed the production line or the heavy vehicles being repaired, sale as it is through the second-hand market; remanufacturing to feed the production line or the heavy vehicles being repaired, sale after remanufacturing as a certified remanufactured part; and material recovery (i.e., recycling).

From the collection and initial diagnosis of the used heavy vehicle, the proposed approach and multi-scale modeling – materialized by a practical data template and its associated spreadsheet detailed hereafter – must be able to: compare different end-of-life scenarios; provide the cost of dismantling and the value that can be recovered according to each possible end-of-life option; and finally, help the industrialist (here the reman. manager) to make the best decision regarding the end-of-life pathways of the recovered components and materials.

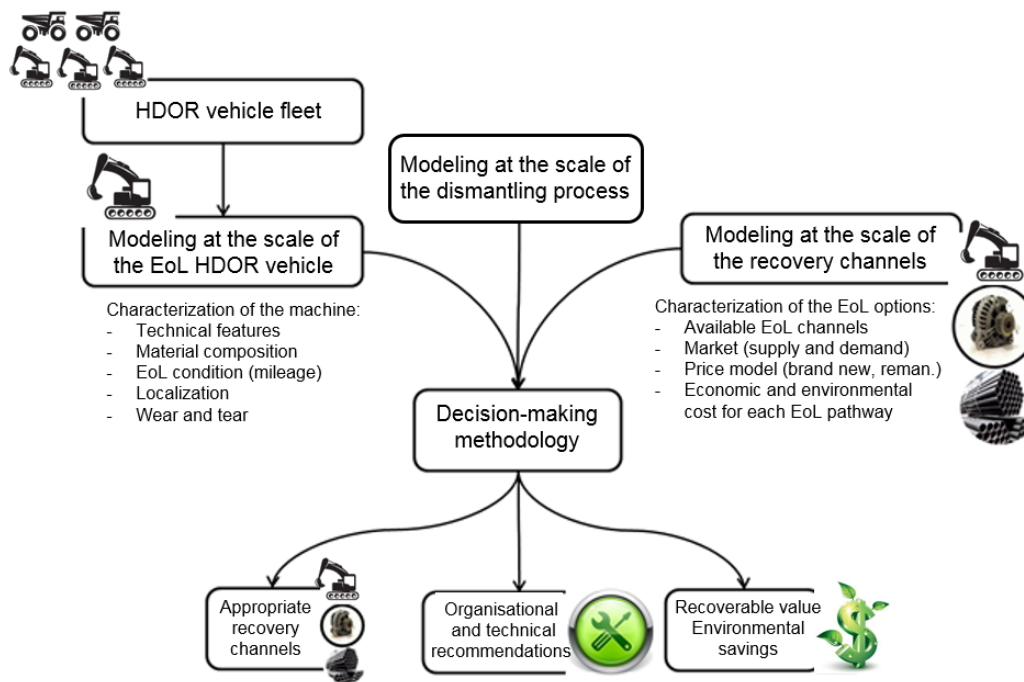


Figure 4 – Schematic view of multi-scale modeling approach including a model of the end-of-life heavy vehicle, the dismantling process and the recovery channels

2.3.2. Data template

Based on the literature review and industrial investigations, a data template has been designed to put together all the elements of information that need to be collected in order to conduct properly both the dismantling experimentation and the technico-economic analysis. The methodology to construct the data template was the following: first, all the elements considered as relevant from the literature survey and ground investigations aforementioned were inventoried. Then, a first draft was presented to the reman. manager to check with him if there were any important missing points and to have this feedback of this first version. Although he valued the completeness of this document, he asked for a more practical version. As such, the data template has been simplified, refined and divided into three separate pages (i.e., one datasheet for each micro-model). A blank version of this data template is available in Appendix A.

More precisely, the purpose of this template is to provide the industrialist with a pre-filled document, facilitating the compilation and exploitation of the data. It includes the sets of technical and organizational parameters to be informed at different levels (end-of-life heavy vehicle and components, dismantling process, recovery channels) in order to carry out the economic and environmental analysis of the recovery of an end-of-life machine, in relation with market constraints and recovery opportunities.

2.3.3. Decision-support spreadsheet

Eventually, to deliver relevant and usable outcomes that fit with the industrial and market realities, the overall model combines complementary micro-models integrated in a single spreadsheet, which characterized quantitatively: the machine and components to be valued, the dismantling process, and finally the possible recovery options and associated value chains. The use of this spreadsheet is further detailed in the sub-section 3.4.

The pre-filled datasheets and spreadsheet have been designed as practical tools to support to the industrialist in answering the following questions: What data are needed? How to compile and use the information to make right economic (and environmental decisions) related to the end-of-life options of a used heavy vehicle and associated components? Particularly, they provide guidelines all along the end-of-management of a heavy vehicle:

- Before the dismantling activity: to be informed of the data that need to be filled in; to complete upstream information that is already known; to be prepared to extract the information during the dismantling;
- During the dismantling operations: to measure and report directly the data requested or to know exactly what to record (videos, photos, notes);
- After the dismantling activity: to fill out the missing data with complementary post-dismantling information; to add any relevant comments.

3. RESULTS: TECHNICO-ECONOMIC AND ORGANISATIONAL RECOMMENDATIONS

3.1. LESSONS LEARNT FROM THE FIRST DISMANTLING OPERATION

A first dismantling experience on an entire end-of-life forklift truck, as detailed in Appendix B and illustrated in Figure B1, has been set up and conducted with the following purposes:

- Mapping and visualization of the current dismantling process;
- Identification of hotspots (e.g., disassembly difficulties, pains for the operator during certain operations);
- Baseline for quantitative improvement of the dismantling process;
- Collection of data (to feed the datasheet/spreadsheet at the scale of the dismantling process);
- Economic analysis of the dismantling cost compared to the remaining value of the recovered components.

In fact, according to discussions with the reman. manager, no dismantling process has been formalized in the past. The disassembly operations are only based on the expertise of the operator and his technical experience, which might be efficient at the beginning but may have room for optimization according to the reman. manager of this remanufacturing center. The idea is that this first dismantling experimentation, from which data are collected and post-treated, would help identifying the areas of improvement to come up with a more systematic dismantling process, optimized or at least enhanced in terms of time and resources used.

This first dismantling operation lasted 5 days with one full-time operator, following the procedure and time illustrated in Figure B2 (see Appendix B). During these 5 days, videos were recorded, photos were taken, and notes reported (including feedbacks from the operator in charge of the dismantling). Based on the post-analysis of all the data collected, an Ishikawa diagram has been proposed to synthesize in an organized and manageable manner all the causes that may have an effect of a poorly efficient and badly dimensioned dismantling process, as depicted in Figure 5.

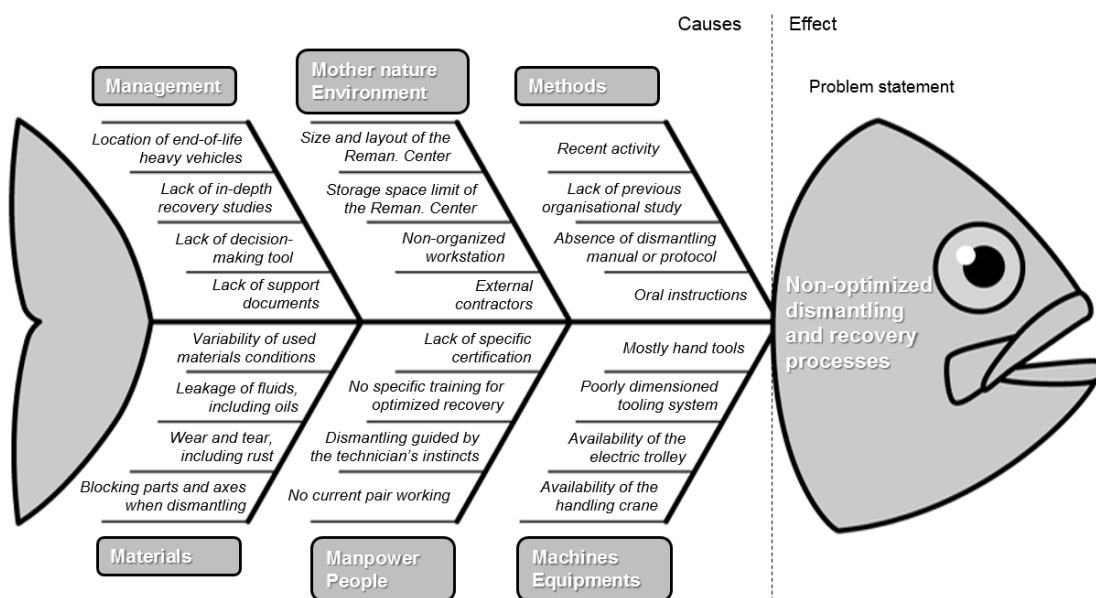


Figure 5 – Ishikawa 6M cause-effect diagram highlighting areas of improvement in the recovery process

3.2. IMPROVEMENT OF THE DISMANTLING PROCESS

Against this background, a two-day workshop has been realized to generate suitable proposals for improvement in the dismantling operations. The expected contribution of this workshop lied is the proposition and detailed design of an enhanced dismantling process in terms of time (to decrease the overall cost of the dismantling operations), efficiency, and comfort for the operator. In accordance with the reman. manager, the room for maneuver and possible levers of actions were: the modification of the current dismantling procedure (operations order, adjustment of lead time), and the possibility to acquire new dismantling resources (materials, tools). To come up with a new feasible dismantling process optimized in time and resources used whilst facilitating the disassembly operations for the technician, best practices from the automotive recycling industry were used as a source of inspiration, as illustrated in Figure 6, with a critical analysis of what is actually transferable to the disassembly of a specific heavy vehicle (forklift truck) as detailed in Table 2. In parallel, the insights provided by the first dismantling test and its post-treatment analysis were used, as well as technical feedbacks from the operator related to its pains during certain disassembly operations and related possible improvement solutions. Also, resources from the International Dismantling Information System (IDIS, 2018), and its section “Equipment for Treatment of ELV” were used to propose new tools that could facilitate the most sensitive or time-consuming disassembly operations. As a result, a new dismantling procedure has been designed, as detailed in Appendix B and displayed in Figure B3, grouping, where possible, the disassembly operations that required the same tooling, and complying with the constraints of predecessors in terms of accessibility.

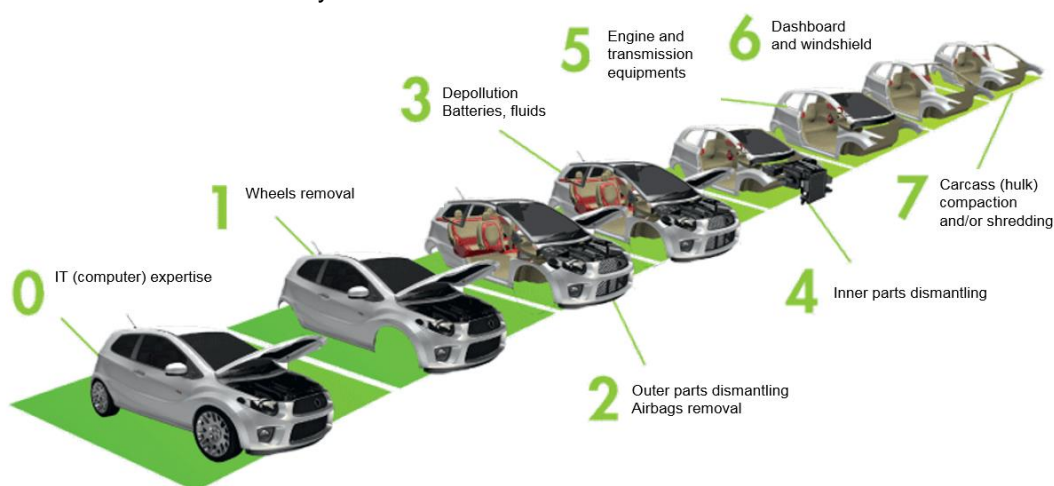


Figure 6 – Streamlined and efficient dismantling process in the automotive industry (source: Indra, 2016, translated from French)

Table 2 – Inspiration and transfer of best practices from state-of-the-art automotive dismantling process

| Characteristics | INDRA automotive recycling | Manitou International Reconditioning Center | Transfer of best practices (adaptation possibilities) |
|-------------------------------------|--|---|---|
| Process Resources Performance | Optimized: 1h30 by end-of-life car; 6 specialized technicians at 6 specific workstations (15 min each); up to 25 cars a day. | Non-optimized: 35h by end-of life heavy machinery, 1 technician; 1-5 heavy vehicles by month. | Re-organization in the dismantling process, resulting in time-saving. |
| Tools | Automatized and pivotable disassembly line, power-driven tools. | Handling crane, handling trolley, standard hand tools. | More fitted tools, better dimensioned, for time-efficiency and technician comfort/safety. |
| Dismantling process steps | #0 IT (computer) expertise, inspection of the vehicle, specific disassembly instructions. | Manual inspection, no computer-based expertise. | Dismantling manual being considered, to support the disassembly. |
| | #1 Wheels removal | Wheels are removed at the end of the dismantling process. | Wheels are kept on the heavy vehicle to ensure his stability. |

| | | | |
|--------------|---|---|--|
| | #2 Outer parts dismantling | Engine crankcase on day 1, engine cap on day 2, cabin on day 3. | To regroup these dismantling operations. |
| | #3 Depollution (batteries, fluids) | Done on day 3, after dismantling all the outer parts, and the arrow, but leads to leakages of fluids the first three days of operations. | Compromise to find: fluids are left to facilitate the move of the arrow, but their leakages are a time and environmental issue. |
| | #4 Inner parts dismantling | Mixed with the dismantling of outer parts, no systematic and repeatable procedure. | Operations that could be mutualized for time-efficiency. |
| | #5 Engine and transmission equipments | Done at the end, in case the heavy vehicle has to be moved. | Positioning in the dismantling process is correct, but the tooling could be better adapted. |
| | #6 Dashboard and windshield removal | Disassembly of the cabin. | Reuse of some parts if needed |
| | #7 Carcass (hulk) compaction and/or shredding | Remaining parts are put in temporary storage bins. | Augmented materials recovery |
| Valorization | Oriented and targeted disassembly, based on the cars' conditions (age, wear and tear, etc.) and the market demand, according to the real-time database of an IT software. | The procedure is not formalized, based on experience, on discussion between the remanufacturing center and other departments of the company. No IT support. | Data template and spreadsheet with the list of components, current stock pricing information, monthly sales, etc. to identify the best recovery options. |

The main modifications (including the order and grouping of several disassembly operations) proposed through the new dismantling process compared to the baseline are highlighted in blue in Figure B3. Notably, we make the assumption that the use of new, specific and more adapted tools could contribute in reducing the lead time of these disassembly operations. As such, the acquisition of the following tools was suggested, as illustrated in Figure B4: a fluid pump connected to a tank of great capacity to drain the fluids more efficiently (depollution operations), a wheeled bin to avoid the leakages of oils on the floor, an hydraulic shear to cut the hoses more quickly, a more handy cordless power tool with Allen sockets extension to reach difficult access components and screws. All the propositions have been validated by the reman. manager and the technician. As a result, we expect a reduction of the overall dismantling time of 22% – from 5 days (33.5 hours) to 4 days (26 hours) – for the next dismantling of a similar forklift truck.

3.3. VALIDATION AND ADJUSTMENT BASED ON A SECOND DISMANTLING EXPERIMENTATION

In order to validate or to adjust the proposed dismantling process, a second supervised and recorded dismantling experimentation has been conducted on a similar 8-ton forklift truck (see Figure B6) with the newly organizational support (timeline of the disassembly operations) and materials support aforementioned to guide and assist the operator in charge of the dismantling. As reported in Figure B5, the reduction of the lead time for several disassembly operations has been reached, resulting in a shift from 5 days to 4 days, or even less (i.e., by splitting the 21 hours of work into 3 days), to dismantle such a forklift truck. Note that while the overall organization by day of the dismantling process has been followed, some minor changes in the order of disassembling some components have been done by the technician for practical reasons. Importantly, feedbacks from the technician confirmed both (i) the new tooling gives him for more comfort and efficiency in the most challenging tasks, and (ii) the fact that having a process to follow allows to be better organized, i.e., not to hesitate about what to do next and therefore to save time. The economic analysis associated to the dismantling operations is detailed in the next sub-section. Also, further promising research areas and industrial improvements (e.g., generalization to other heavy vehicles, design of a detailed dismantling manual) are finally discussed.

3.4. PREFERRED RECOVERY OPTIONS IN A CIRCULAR ECONOMY PERSPECTIVE

A spreadsheet has been designed to assist the industrialist (here the Reman. Center) in selecting the best end-of-life options for the components recovered after the dismantling, regarding economic (profit), environmental (impact) and marketing (stock/demand) aspects. An extract of the spreadsheet is provided in

Figure 7. Note that this decision support tool has been developed French, but the key sections are schematically explained below in English. Also, sensitive data (e.g., mass, costs, stock, demand) of this specific industrial case study are hidden for confidentiality purposes.

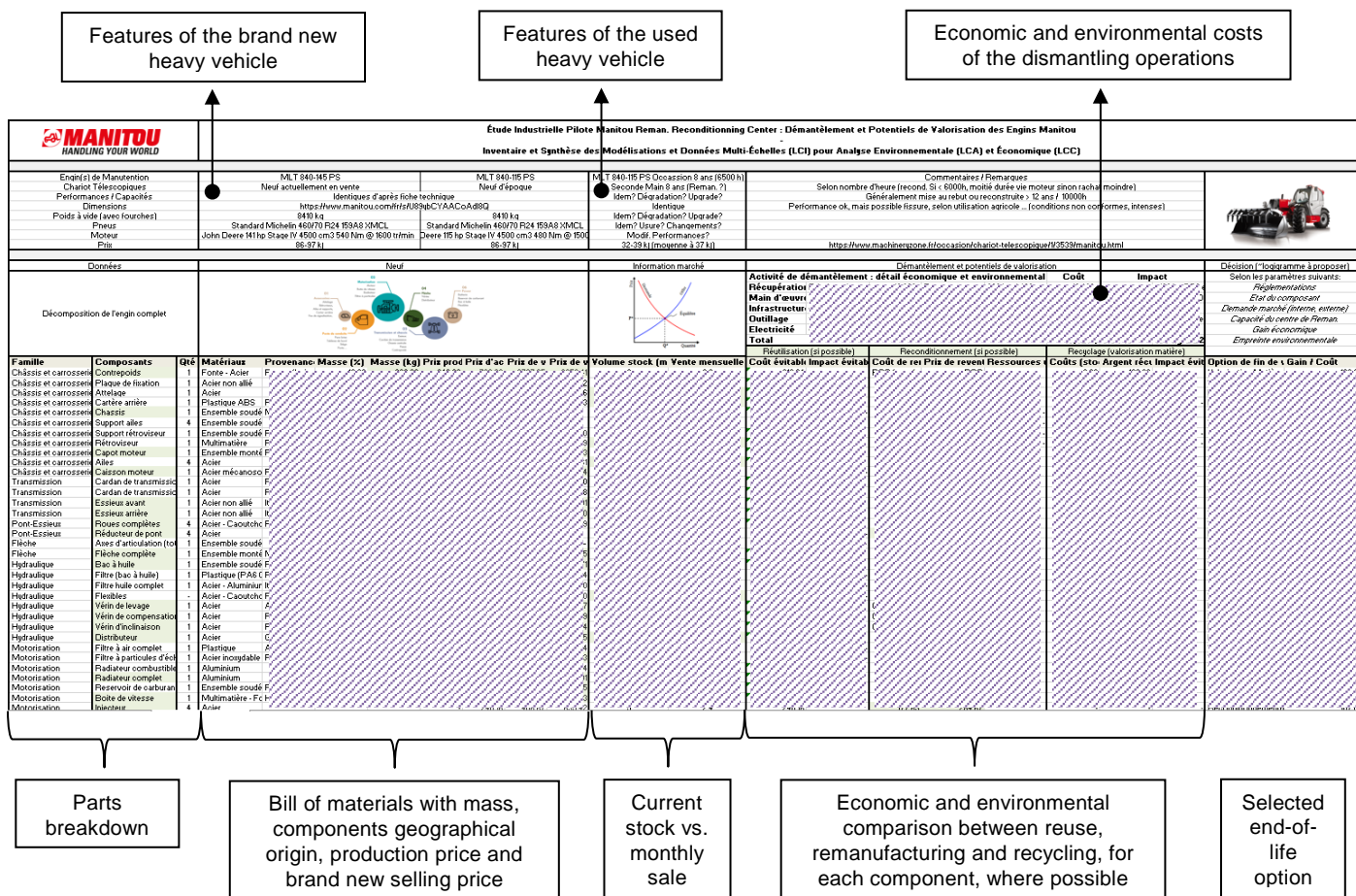


Figure 7 – Snapshot of the spreadsheet to select preferred CE loops for the recovered components of an EoL heavy vehicle (sensitive cells have been purposely blurred for confidentiality purposes)

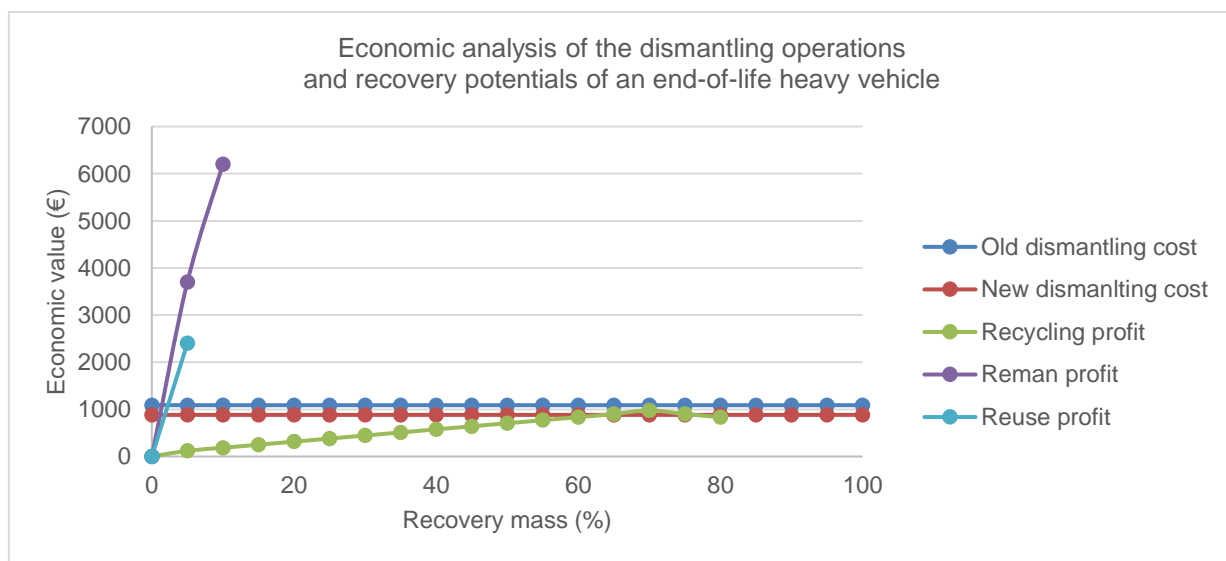


Figure 8 – Economic analysis: cost of dismantling and benefits from reuse, reman, and material recovery

This spreadsheet puts together the three micro-models detailed in sub-section 2.2, and following the data template, it combines data coming from complementary sources: (i) modelling of the used heavy vehicle and related components (data coming from the design department and the reman. center); (ii) modelling of the dismantling process (data coming from the experimentation within the reman. center); (iii) and modelling of the recovery channels (data coming from the reman. center, and from independent research) and the market demand (data coming from the sales department, and from the parts and services department).

Based on the data collected from the aforementioned departments, it has been possible to conduct a first economic analysis, while other complementary data are needed to perform an environmental evaluation as well. For each component with a recovery potential, an economic analysis is made comparing the additional processing effort and the recoverable economic value related to the possible end-of-life options. Particularly, to evaluate the profitability of remanufacturing some key components, a comparison is also made with the costs of manufacturing new products.

All in all, to be profitable, the sum of all the economic recovery potentials (i.e., profit from recovered spare parts and material recycling) has to be superior to the cost of the dismantling operation, plus the buy-back price of the end-of-life heavy vehicle. The dismantling costs include the: workforce and supervision, amortization of the building and tools, electricity and consumables. Note that the improvement of the dismantling process, in terms of time, combined with the acquisition of new tools, allow to slightly reduce the cost of one dismantling operation as illustrated in Figure 8.

Figure 8 shows that while the profit made by material recovery enables to offset the dismantling cost, the company has a strong interest in further considering the reuse and remanufacturing of parts which are the most cost-effective solutions. On this basis, the company is currently conducting some “proof of concept” studies to evaluate the technical and economic feasibility of remanufacturing other key components.

As displayed in Figure 8, the X-axis corresponds to the recovery mass, demonstrating it is possible to reach the minimum and mandatory targets of the ELV Directive 2000/53/EC, with presently a material recovery mass of 80% of the entire heavy vehicle, while components remanufacturing and reused represent respectively around 10% and 5%, for a total of almost 95%. Note also that the material recovery is profitable up to 75% of the mass of the heavy vehicle (mainly steel and aluminum) and the 5% remaining are a cost for the reman. center (sub-contractors in charge of the handling of special substances recovery).

According to discussions with the reman. manager, the spreadsheet is both comprehensive and practical for him. Moreover, even we have to bear in mind if the results from the present economic analysis may significantly vary from a used heavy vehicle to another, such results provide a strong basis to assess the conditions of an extension of their remanufacturing activities, as well as to negotiate the buy-back price of a used machinery based on its actual recovery potential.

4. CONCLUSION: REMAINING CHALLENGES AND PROMISING FUTURE RESEARCH

Lessons learnt from this industry case study open up on broader implications for an overall sound end-of-life management of heavy vehicles, enabling thus further CE activities. In this conclusion section, the promising future research and industrial challenges to achieve a more advanced CE in the heavy vehicle industry are discussed in sub-section 4.1. Note that this research was limited by one in-depth industrial pilot study case, including two dismantling experimentation, a workshop and feedbacks from industrialists. As such, further research is desirable to investigate how the proposed approach, improvement solutions, and developed support tools (data template and spreadsheet) could be adapted, generalized and/or reused to support the end-of-life management of other types of heavy vehicles (sub-section 4.2).

4.1. ADVANCING CIRCULAR ECONOMY PRACTICES IN THE HEAVY VEHICLE INDUSTRY

This industrial pilot study, conducted in collaboration with a heavy vehicle manufacturer and its emerging remanufacturing center, provides promising results regarding the feasibility, as well as the profitability – under certain conditions – of a supervised dismantling and recovery of end-of-life heavy vehicles, and therefore can foster similar practices at a wider scale. In the long run, we encourage similar industrial experimentations and believe they can be an entry point before the setting up and operational implementation of an end-of-life regulation. Also, by showing concrete opportunities of value creation in the end-of-life management of heavy vehicles, it is hoped that such studies can contribute in raising the interest of other industrial stakeholders –

including OEMs, end users, EoL facilities – in maintaining the end-of-life heavy vehicles within the EU to be properly dismantled and recovered.

Actually, the insights provided both by this industrial case study can foster businesses of the heavy vehicle industry in implementing more and more circular strategies, projects and practices. We argue that industrialists (managers, designers, engineers, operators, technicians) can use this knowledge to accelerate their transition towards a more CE. Concretely, Manitou is taking its Remanufacturing Center to the next level by prototyping a first dismantling manual as illustrated in Figure 9, and by increasing the communication about their end-of-life solutions.

More generally, further research and investigations are truly encouraged to move from an industrial pilot study to a full-scale industrial deployment of sound end-of-life management practices in the heavy vehicle industry, considering economic (profitability), environmental (impact savings), technical (feasibility, circular design), organizational (processes, collaborations, reverse supply chain) and political (regulations) aspects. For instance, next steps and/or further work could include:

- Environmental impact analysis of the dismantling operations and environmental impact comparison between the production of remanufactured and newly manufactured components. For example, Xiao et al. (2018) compared the environmental performance of manufactured and remanufactured loading machine in China: they used the life cycle analysis (LCA) methodology to compare the environmental impacts and cost of a manufactured loading machine (S1) with its remanufactured counterparts under two return-back scenarios: remanufacturing at the original factory (S2) and at regional dealers (S3). The results showed that climate change effects of S1, S2 and S3 were 4.4t, 1.3 t, 0.92 t CO₂-eq respectively. In this line, future research should be fostered to systematically quantified the environmental impacts of implementing a remanufacturing strategy, so as to prevent any potential environmental impact transfer.
- Uncertainties in the quantity and quality of returned heavy vehicles collected for remanufacturing. For example, Aydin et al. (2018) proposed a methodology to determine the optimal product returns for remanufacturing with consideration of the uncertainty in the quantity and quality of returns. The develop model studies not only the effects of new product sales and demand for remanufactured products on used product returns, but also the effects of quality of returns on the remanufacturing cost. Yet, their approach and developed models have to be applied and experimented on more complex industrial cases such as the end-of-life management of heavy vehicles and associated key components.
- Flexibility in the dismantling process: to evolve from a systematic and improved dismantling process to a smart and optimized one, according to the initial diagnosis of the recovered heavy vehicle and components, the market demand and internal capabilities; to integrate the micro-models proposed into a system engineering platform/software so as to explore systematically the configurations of the disassembly sequence, in link with the available recovery channels of heavy machinery components.
- Eco-design, modular and circular design considerations, based on the dismantling hotspots identified, for the future development of heavy vehicles in order to facilitate their disassembly, remanufacturing and end-of-life recovery. In the present case study, a feedback has been made to the design department so as to feed their current eco-design checklist.
- Investigation on the location of used and end-of-life heavy vehicles at a regional and national level: it is indeed an essential aspect to ensure the proper collection of such vehicles. Solutions include product-service systems (PSS) related business models to keep the ownership of the heavy vehicle, and/or the use of sensors and telematic systems to allow the traceability, plus preventive maintenance, of the machine during its use.
- Reflexion on the possibility to extend the ELV Directive 2000/53/EC to the heavy vehicle industry, including the implementation of an extended producer responsibility (EPR) scheme for this industrial sector. The support of an end-of-life regulated framework is indeed highly commendable, e.g., to avoid illegal exports and to ensure the supply of sufficient quantity of used heavy vehicles in sound EoL centers.



Figure 9 – Illustrations of the dismantling manual under development (source: Manitou Reman)

4.2. TRANSFER OF BEST CIRCULAR ECONOMY PRACTICES FROM ONE INDUSTRY TO ANOTHER

Throughout this industrial pilot study, the concrete transfer and practical application of best circular practices and know-how from one industrial sector to another was closely considered. The objectives were not only to bring real and well-documented contributions for the heavy vehicle industry in its move towards more circular practices but also test and validate the conditions of transfer of commendable remanufacturing practices from the automotive industry to the heavy vehicle one. Interestingly, commendable practices from the automotive recycling industry have been used to improve the dismantling process of an end-of-life heavy vehicle in a remanufacturing center. The potential generalization and adaptation of the approach, including models and tools detailed in this article, and applied to the heavy vehicle remanufacturing industry, to other industries that are facing similar challenges in their transition to a more circular economy is also a line of research that can be further investigated. For instance, investigating to what extent the research advances, policy framework, and industrial practices that support the circular economy in the automotive industry could be transferable or adapted to other sectors, such as the aircraft industry for a more sustainable end-of-life management of its fleet (Saidani et al., 2019).

Actually, in the “closed loop” CE research model, it is critical to continually test the real-world implementation of theoretical CE tools, while at the same time using findings and challenges illuminated by applications to generate new research questions (Babbitt et al. 2018). Particularly, as detailed in the previous sub-section, this article shed some lights on the remaining challenges the heavy vehicle industry must address to reach an efficient, effective, and sustainable CE but also provide concrete recommendations. In this line, future works are encouraged where academic and industry tenants collaborate and contribute together in supporting the shift towards more circular and sustainable practices. Communication of commendable practices (including latest research developments or industrial experimentations), between researchers and industrialists concerned with the challenges and opportunities, are of the utmost importance to take remanufacturing practices to the next level in a circular and sustainable perspective.

We argue that the insights (including the economic analysis) provided by this industrial pilot study can stimulate other industrial players in the development of their remanufacturing strategy. Practically, the approach used in this pilot study could also serve as a relevant basis for the development of more advanced frameworks and tools aiming at measuring, improving and monitoring the performance (technical, economical

and organizational) of a remanufacturing process in other industry. Indeed, this study, conducted in close collaboration with an emerging remanufacturing center manuscript provides practical implications and guidance with examples for both (i) industrial practitioners – engineers, designers, managers, operators – willing to implement/manage/improve the remanufacturing process of their product; and (ii) researchers, interested in the technical, economic and organizational environmental dimensions of remanufacturing, who are eager to develop practical remanufacturing frameworks (including tools, technico-economic and environmental analysis) that fit with industrial needs.

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APPENDIX A - DATA TEMPLATE TO SUPPORT THE END-OF-LIFE MANAGEMENT OF HEAVY VEHICLES

DATASHEET AT THE SCALE OF THE END-OF-LIFE HEAVY VEHICLE

CHARACTERIZATION OF THE MACHINE

- ✓ Reference and type of machine:
- ✓ Nomenclature and/or technical datasheet, if available:
- ✓ Selling price of the brand-new equipment vs. total cost of manufacturing
- ✓ Range price on the second-hand market
- ✓ Age and mileage of the worn-out machine:
- ✓ Condition of the recovered machine (wear and characterization): Intact – Accidented – End of life – Obsolete
- ✓ Degree of functionality: Still operational but dismantling for what reason(s) – Overall performance degradation Important wear and tear of some components
- ✓ Traceability during use (e.g., change of parts) if any:

CHARACTERIZATION OF KEY COMPONENTS

What are the key components of the machine?

It can be a component that includes one or several of the following characteristics: {high economic value; heavy mass; greater environmental impact; core product technology; technological, manufacturing or assembly complexity that requires a strong expertise; significant manufacturing time; bottlenecks; high specificity or high transversality}.

- Outer components: bodywork, doors, windows, lenses, bumpers, lights, tires
- Inner components: seats, control instruments, electronics, etc.
- Transmission systems: different fluids (transmission fluid, brake fluid, engine oil, petrol), batteries, engine, transmission (differential, gearboxes), chassis, catalytic converters, etc.
- Special equipment for handling operations: platforms, telehandlers / elevators, forks, etc.

| Key components # | Mass / Materials Prices (brand new, buying to suppliers, selling to users) | Conditions (wear and tear, functional, etc.) | Accessibility and ease of dismantling (1 = Easy ; 4 = Difficult) | Transversality (compatibility with other machines) | Reuse or reman. opportunities? | Possible do to so at the Reman. Center? |
|------------------|--|--|--|--|--------------------------------|---|
| | | | | | | |
| | | | | | | |
| | | | | | | |
| ... | | | | | | |

To close-the-loop effectively and efficiently, it is suitable to know what are the components and materials that have to be dealt with, in order to identify and select appropriate second-hand uses, e.g., by considering the cost of different possible EoL options and to the value recoverable associated to these potential EoL pathways.

DATASHEET AT THE SCALE OF THE DISMANTLING PROCESS

PRE-DISMANTLING INFORMATION

- Reverse logistic aspects: distance, mean of transportation and cost to return the used machine to the Reman. Center:
- Current dismantling process, including steps and time: (illustrations or guidance documentation, if available)

What are the similarities and differences with the standardized, streamlined and well-established dismantling and recovery process (see figure below) of an ELV in Europe? (regulated by the European Directive 2000/53/EC)

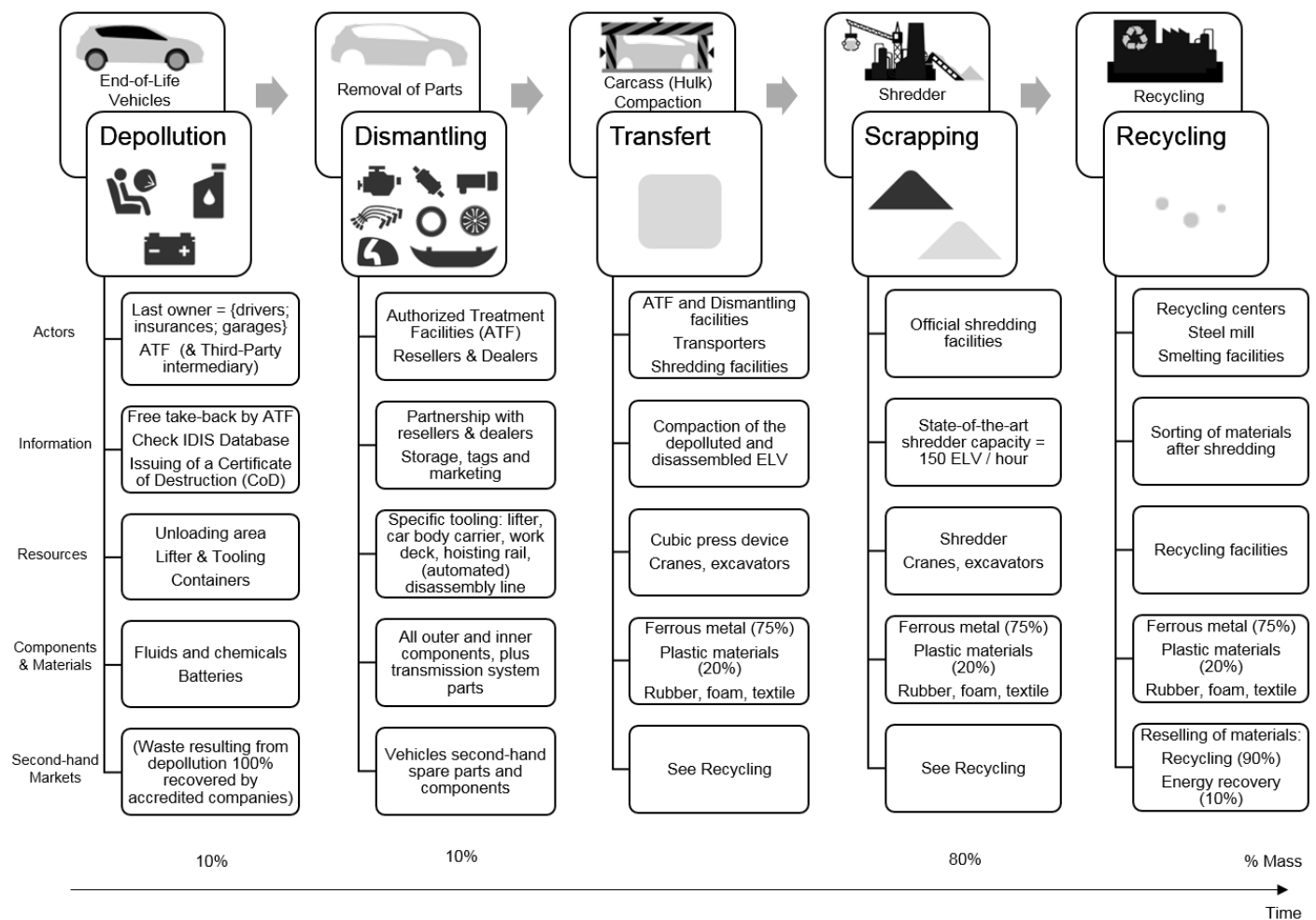


Figure A1 – End-of-life vehicle processing in the automotive industry, based on Toyota (2016) plus additional sources of information (INDRA, 2016; Directive 2000/53/EC) and consulted experts

What resources are available and mobilized for the dismantling operations? (equipment, tools, labor and skills). If possible, indicate the associated economic (price, ...) and environmental costs (energy...)

Do you already know the fate of some components that will be dismantled from the machine?

DISMANTLING PROCESS (EQUIPMENTS, OPERATIONS, ACTIVITIES)

Disassembly sequence: fill in the table below, if possible add photos or videos highlighting the dismantling hotspots.

| Operation # | Component(s) | Time | Resources used | Energy consumption, etc. |
|-------------|--------------|------|----------------|--------------------------|
| ... | | | | |

- Classification mode of the disassembly operations: partial or total; targeted/selective/flexible or systematic; destructive or non-destructive ? (number of components or parts concerned for each case)
- Total duration of disassembly operations:
- Total cost of the dismantling activity, including: workforce, supervision, electricity, tooling depreciation, infrastructures, cost of storage, other recycling cost (e.g., handling of hazardous substances)
- Total energy consumption (electricity, machine power supply, etc.):
- Difficulties encountered, including: accessibility, positioning, force required, time required, persons required:
- Access to key components facilitated by design or a dismantling guide / repair manual?
- Disassembly points easily recognizable: No – Yes but damaged by wear and tear – Yes

POST-DISMANTLING INFORMATION

After the inspection and sorting of the recovered components, the information in the table below will help defining the best end-of-life options for second-hand components and/or materials.

| Recovered component # | Conditions: second-hand part price, recoverable value of materials | Reusable as it is (for which purpose?) | Further disassembly envisaged? | Possible to Remanufacture? |
|-----------------------|--|--|--------------------------------|----------------------------|
| ... | | | | |

Characterization of the rest of the machine (components remaining, ready to be refurbished?), if partial dismantling:

DATASHEET AT THE SCALE OF POSSIBLE END-OF-LIFE OPTIONS

| Recovery channels/options # | Components and materials concerned | In stock quantity vs. demand (current or forecast) | Costs of the operation (eco, env) Potential benefits | Subcontractor Location |
|--|--|--|--|------------------------|
| Internal reuse | <i>Examples: Tires, depending on the wear and tear</i> | | | |
| Resale as second-hand parts | Some outer components | | | |
| Remanufacturing to reach conformity then option # 1 or 2 | <i>Gearbox / motor / alternator / turbo / injector / gearbox</i> | | | |
| Material recovery | <i>Steel / aluminum / copper / plastics / miscellaneous fluids (oils, liquids ...)</i> | | | |

APPENDIX B – TECHNICAL DETAILS OF THE DISMANTLING PROCESSES



Figure B1 – Photos of the first dismantling test (baseline)

Non-optimized dismantling process in time and resources (Manitou Reman, February 2018)

| ID | Task Name | Predecessors (Enter one ID per cell) | Time in hours | | | Durati on | ES | EF | LS | LF | Slack |
|-----|--|---|---------------|------------|------------|--------------|-------|-------|------|------|-------|
| | | | O (min) | M (max) | P (max) | | | | | | |
| 10 | Start | | | | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 20 | Rear crankcase + Lighting + Mirror | 10 | 2.5 | 2.5 | 2.5 | 2.50 | 0.00 | 2.50 | 0.00 | 0.00 | 0.00 |
| 30 | Wings + Hitch | 20 | 2 | 2 | 2 | 2.00 | 2.50 | 4.50 | 0.00 | 0.00 | 0.00 |
| 40 | Balance | 30 | 2 | 2 | 2 | 2.00 | 4.50 | 6.50 | 0.00 | 0.00 | 0.00 |
| 50 | Engine cap | 40 | 1.5 | 1.5 | 1.5 | 1.50 | 6.50 | 8.00 | 0.00 | 0.00 | 0.00 |
| 60 | Lifting cylinder + Compensator | 50 | 1 | 1 | 1 | 1.00 | 8.00 | 9.00 | 0.00 | 0.00 | 0.00 |
| 70 | Arrow + Inclination actuator | 60 | 3 | 3 | 3 | 3.00 | 9.00 | 12.00 | 0.00 | 0.00 | 0.00 |
| 80 | Hydraulic hoses | 70 | 1.5 | 1.5 | 1.5 | 1.50 | 12.00 | 13.50 | 0.00 | 0.00 | 0.00 |
| 90 | Wires + Cabin | 80 | 3 | 3 | 3 | 3.00 | 13.50 | 16.50 | 0.00 | 0.00 | 0.00 |
| 100 | Battery + Draining oils + Reservoir tank | 90 | 5 | 5 | 5 | 5.00 | 16.50 | 21.50 | 0.00 | 0.00 | 0.00 |
| 110 | Filters + Distributor | 100 | 2 | 2 | 2 | 2.00 | 21.50 | 23.50 | 0.00 | 0.00 | 0.00 |
| 120 | Radiators | 110 | 2 | 2 | 2 | 2.00 | 23.50 | 25.50 | 0.00 | 0.00 | 0.00 |
| 130 | Hoses and engine wires | 120 | 2 | 2 | 2 | 2.00 | 25.50 | 27.50 | 0.00 | 0.00 | 0.00 |
| 140 | Transmission axis and shaft | 130 | 1 | 1 | 1 | 1.00 | 27.50 | 28.50 | 0.00 | 0.00 | 0.00 |
| 150 | Motor and gear box | 140 | 2 | 2 | 2 | 2.00 | 28.50 | 30.50 | 0.00 | 0.00 | 0.00 |
| 160 | Wheels | 150 | 1 | 1 | 1 | 1.00 | 30.50 | 31.50 | 0.00 | 0.00 | 0.00 |
| 170 | Rear and front axles + Chassis | 160 | 2 | 2 | 2 | 2.00 | 31.50 | 33.50 | 0.00 | 0.00 | 0.00 |
| 180 | End | 170 | | | | 0.00 | 33.50 | 33.50 | 0.00 | 0.00 | 0.00 |

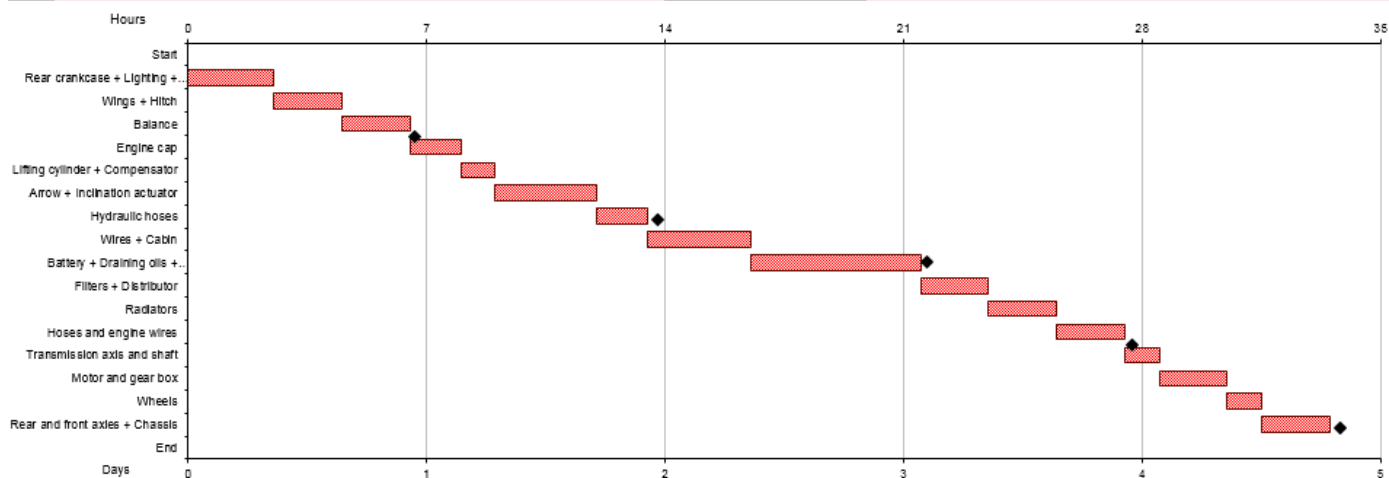


Figure B2 – Gantt chart of the dismantling process before improvement (baseline)

Proposition of a new dismantling process, improved in time and resources use

| ID | Task Name | Predecessors (Enter one ID per cell) | Time in hours | | | Duration | ES | EF | LS | LF | Slack |
|-----|--|---|---------------|-------------|------------|----------|-------|-------|------|------|-------|
| | | | O (min) | M (hour) | P (max) | | | | | | |
| 10 | Start | | | | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 20 | Day 1: Outer components (using standard hand tools + electric trolley at the end of) | 10 | 7 | 7 | 7 | 7.00 | 0.00 | 7.00 | 0.00 | 0.00 | 0.00 |
| 30 | Rear crankcase + Lighting + Mirror | 10 | 2 | 2 | 2 | 2.00 | 0.00 | 2.00 | 0.00 | 0.00 | 0.00 |
| 40 | Wings + Hitch | 30 | 2 | 2 | 2 | 2.00 | 2.00 | 4.00 | 0.00 | 0.00 | 0.00 |
| 50 | Motor cap | 40 | 15 | 15 | 15 | 15.00 | 4.00 | 5.50 | 0.00 | 0.00 | 0.00 |
| 60 | Balance | 50 | 15 | 15 | 15 | 15.00 | 5.50 | 7.00 | 0.00 | 0.00 | 0.00 |
| | Day 2: Heavy components (using handling crane + new tools for cutting the hoses) | 60 | 7 | 7 | 7 | 7.00 | 7.00 | 14.00 | 0.00 | 0.00 | 0.00 |
| 70 | Lifting cylinder + Compensator | 60 | 1 | 1 | 1 | 1.00 | 7.00 | 8.00 | 0.00 | 0.00 | 0.00 |
| 80 | Arraw + Inclination actuator | 70 | 3 | 3 | 3 | 3.00 | 8.00 | 11.00 | 0.00 | 0.00 | 0.00 |
| 90 | Hydraulic hoses | 80 | 15 | 15 | 15 | 15.00 | 11.00 | 12.50 | 0.00 | 0.00 | 0.00 |
| 100 | Cabin (dashboard, etc.) | 90 | 15 | 15 | 15 | 15.00 | 12.50 | 14.00 | 0.00 | 0.00 | 0.00 |
| | Day 3: Complete depollution (using new pumps and well-dimensioned containers) | 100 | 7 | 7 | 7 | 7.00 | 14.00 | 21.00 | 0.00 | 0.00 | 0.00 |
| 110 | Battery + Draining oils + Fuel tanks | 100 | 3 | 3 | 3 | 3.00 | 14.00 | 17.00 | 0.00 | 0.00 | 0.00 |
| 120 | Filters + Distributor | 110 | 2 | 2 | 2 | 2.00 | 17.00 | 19.00 | 0.00 | 0.00 | 0.00 |
| 130 | Radiator | 120 | 2 | 2 | 2 | 2.00 | 19.00 | 21.00 | 0.00 | 0.00 | 0.00 |
| | Jour 4 : Engine system (using adapted e.g. handle extension Allen socket) | 130 | 6 | 6 | 6 | 6.00 | 21.00 | 27.00 | 0.00 | 0.00 | 0.00 |
| 140 | Hoses + Wires | 130 | 1 | 1 | 1 | 1.00 | 21.00 | 22.00 | 0.00 | 0.00 | 0.00 |
| 150 | Engine and gear box | 140 | 15 | 15 | 15 | 15.00 | 22.00 | 23.50 | 0.00 | 0.00 | 0.00 |
| 160 | Transmission axis and shaft | 150 | 0.5 | 0.5 | 0.5 | 0.50 | 23.50 | 24.00 | 0.00 | 0.00 | 0.00 |
| 170 | Wheels | 160 | 1 | 1 | 1 | 1.00 | 24.00 | 25.00 | 0.00 | 0.00 | 0.00 |
| 180 | Rear and front axles + Chassis | 170 | 2 | 2 | 2 | 2.00 | 25.00 | 27.00 | 0.00 | 0.00 | 0.00 |
| 190 | End | 180 | | | | 0.00 | 27.00 | 27.00 | 0.00 | 0.00 | 0.00 |

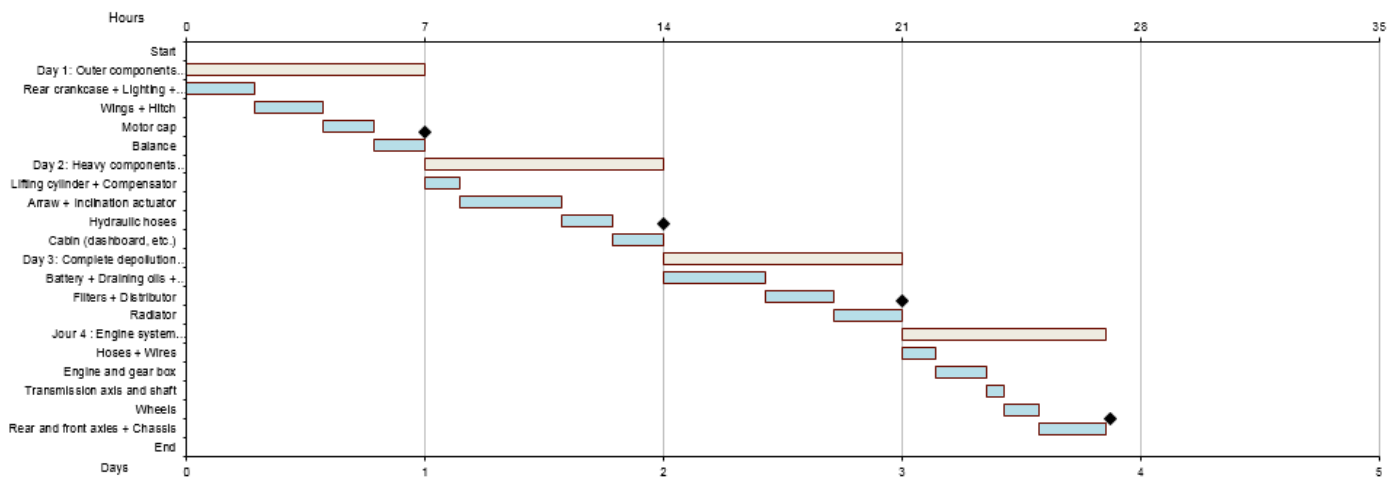


Figure B3 – Gantt chart of the newly proposed and adjusted dismantling process



Figure B4 – Photos of the tools recommended and acquired to smooth the dismantling process

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Validation and adjustment of the proposed dismantling process (Manitou Reman, June 2018)



Figure B5 – Gantt chart of the newly validated dismantling process after a second dismantling test



Figure B6 – Photos of the second and sound organized dismantling operation