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End-of-life decision-making framework for automotive vehicles

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End-of-life Decision-making Framework for Automotive Vehicles

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Scope of Work

End-of-life Decision-making Framework for Automotive Vehicles

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Status Quo:

Sales in the automotive market have soared worldwide in recent decades, mainly due to reduced vehicle manufacturing costs (HAMILTON 1999, p. 1). The major automotive brands have focused their efforts on meeting the emerging demand with new cars, always produced from scratch. Taking advantage of already used pieces and materials has been extensively studied recently. This is mainly due to the new collective awareness regarding the care of the planet and the economic advantage of reducing the exploitation of raw materials and the manufacture of new parts.

The new approach, therefore, focuses on sustainability and its three key pillars: economic, social, and environmental. In this context, concepts such as Circular Economy are gaining strength. The idea of Circular Economy reinforces these three concepts, conserving environmental and economic resources (such as materials, energy, labour, and capital value) incorporated into products and contributing to the social dimension of sustainability. To achieve a circular economy in production, closed loops must be created. Closed-loop supply chains are supposed to recover value from product returns and are usually dominated by a central actor who intends to control the entire product lifecycle (KALVERKAMP 2018, pp. 159-161). A vehicle that has theoretically reached the end of its life cycle can be returned to the conditions under which it was produced by following different strategies. These strategies include repair, refurbishment, remanufacturing, and repurposing. This means less exploitation of raw materials and reduced emissions and costs of producing a vehicle from scratch. The total or partial disassembling of ELVs may be required to create closed material loops. Deciding in this regard is a vital and understudied process.

The main objective of this Thesis is the development of a structured evaluation system to decide whether the best option for a vehicle or a vehicle part at the end of its life is to disassemble or scrap it. The system will use Key Performance Indicators (KPIs) to define the vehicle's status to achieve this goal. The result of implementing this system should be sufficient to discern whether disassembling the analysed vehicle or part is the best option.

Scope:

This thesis aims to develop a system to assess whether the best option for a vehicle, or a part of it, at the end of a life cycle is to disassemble or scrap it. For this purpose, KPIs will be used to define the vehicle's status.

RQ1: What analysis is currently carried out to determine whether a vehicle is disassembled or scrapped?

RQ2: Which KPIs are necessary to decide between disassembling or scrapping the vehicle?

RQ3: What would a system look like that, using the necessary KPIs, would assess whether the best option is to disassemble the vehicle or any of its parts, or to scrap it?

RC1: Analysis of current methods for decision-making related to disassembling in the automotive industry.

RC2: Review of current KPIs focused on end-of-life vehicle decision-making.

RC3: Development of a framework to help decide whether a vehicle or any of its parts should be disassembled or scrapped.

Approach:

- Acquisition of knowledge in the field of sustainability applied to the automotive sector.
- Familiarisation with the processes currently used for end-of-life decision-making in the automotive industry.
- Analysis of the KPIs described in the literature applied to end-of-life decision-making.
- Development of new specific KPIs focused on the decision to disassemble cars.
- Creation of a structured system that brings together the KPIs relevant to the decision to disassemble.
- Application for system validation in a simulated example.

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Garching, 16.05.2023

Prof. Dr.-Ing. Michael F. Zäh	B.Sc. Miguel Carballar

References:

Bruce W. Hamilton, Molly K. Macauley (1999): Heredity or Environment: Why is Automobile Longevity Increasing?

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Abstract

The application of the Circular Economy (CE) concept to the automotive industry has been extensively examined in recent decades. Decision-making concerning end-of-life vehicles (ELVs) plays a pivotal role in promoting the circularity of components and materials. However, typically, only those vehicle components mandated by law for removal by Original Equipment Manufacturers (OEMs) are disassembled from ELVs. This Master's Thesis investigates CE implementation in the current state of the automotive industry and recent research in the context of end-of-life (EOL) product decision-making. After this analysis, a Decision-Making Framework (DMF) has been developed, focused on evaluating disassemble parts from ELVs.

The DMF employs an Analytic Hierarchy Process (AHP), a Fuzzy Multi-criteria Decision-Making (MCDM) method, and Key Performance Indicators (KPIs) to assess individual parts within a vehicle component, determining whether each should be remanufactured, recycled, or scrapped, based on technical suitability, and environmental and economic performance. This assessment combines objective data with the subjective input of industry and literature experts. The application of the DMF aims to inform ELV treatment decision-makers about the appropriateness of disassembling a particular part. The DMF's validation involved applying it to the left front door of a BMW 5 Series. The results indicate that four out of the ten components, into which the door was subdivided, should be remanufactured, while the remaining six should be recycled, thus justifying the disassembly of this part into its components for treatment.

Keywords: Circular Economy; decision-making; ELV; Remanufacturing; AHP; Fuzzy MCDM

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46 Emissions, energy consumed and economic benefit resulting from the DMF implementation

III List of Abbreviations

AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
ASR	Automotive Shredder Residue
CE	Circular Economy
CI	Consistency Index
CR	Consistency Ratio
DEMATEL	Decision-making Trial and Evaluation Laboratory
DfRem	Design for Remanufacturing
DMF	Decision Making Framework
ELV	End-of-life Vehicle
EOL	End-of-life
EPA	Environmental Protection Agency
EU	European Union
ISM	Interpretive Structural Modelling
KPI	Key Performance Indicator
MCDM	Multi-criteria Decision-making
OEM	Original Equipment Manufacturer
RI	Random Inconsistency
WARM	Waste Reduction Model

IV List of Symbols

C_f	Cost of fastener failure	€
C_P	Cost of part failure	€
C_{raw}	Raw materials’ cost	€
C_{rm}	Remanufacturing cost	€
f	Disassembly depth factor	-
L	Labour rate	*€/min*
L_d	Labor rate of disassemblers	*€/min*
L_r	Labor rate of restorers	*€/min*
P_f	Probability of fastener failure in disassembly and assembly	-
P_{pd}	Probability of part failure in disassembly and assembly	-
P_{pe}	Probability of part failure in fastening method extraction	-
T_a	Assembly time	*min*
T_d	Disassembly time	*min*
T_r	Pieces’ restorage and reassembly time	*min*

1 Introduction

According to European Union (EU) data (European Union, 2010), several reasons have led to an increase in the level of waste produced per capita by European citizens. This source reviews some of these reasons and their consequences. The most notorious is the increase in living standards on the continent and consequently the increase in consumption. There are also more single-person households, which is usually related to more waste than a family or group per capita. The increase in waste is also related to a greater variety of products, many of them disposable or designed to have a short shelf life. Inadequate management of this waste can have a significant impact on the environment, but also on the economy and society. Its disposition can contribute to soil, water and air pollution, endangering human, and other species' health. Incineration - whether for energy recovery or not - contributes to the emission of greenhouse gasses and therefore plays a fundamental role in climate change. Producing a greater amount of waste leads also to the depletion of valuable resources. Numerous materials found in waste, including plastics, metals, and paper, demand substantial energy and resources during their manufacturing process. The escalation in waste generation intensifies the utilization of raw materials and exacerbates their scarcity.

From an economic standpoint, managing and disposing of waste requires financial resources. As seen in Hunt et al. (1997), increased waste generation puts a burden on waste management systems, requiring investments in infrastructure, transportation, and treatment facilities. These costs are often borne by governments, businesses, or individuals. This is disregarding the opportunity cost associated with producing new components from previously utilized parts or materials. Waste can have social consequences, particularly in communities near waste disposal sites. These areas may suffer from reduced property values, increased noise and traffic, and potential stigma associated with being located near waste facilities (Vasarhelyi, 2021).

A material becomes waste when it is discarded without expecting to be compensated for its inherent value (Misra & Pandey, 2005). For the reasons mentioned above, it is important to prevent products or their components from being classified as waste. In the line with the research conducted by Kalverkamp et al. (2018), establishing closed-loop supply chains reduces the amount of waste generated by the industry, thereby avoiding environmental, economic, and social issues associated with their waste status. Moreover, it contributes to the preservation of raw materials, economic resources, and energy that would otherwise be expended during their production from the ground up. It can be concluded that the way to prevent a product from reaching the waste state is by preserving or recovering its inherent value. Every time a product that had lost its utility is regained; a loop has been closed.

Certainly, there are different states in which a product can return to the hands of a consumer, and conditions that resemble factory-like characteristics will always be preferable, although it is not always attainable. Often, the end-of-life (EOL) treatment of a product involves downcycling, where the original factory characteristics or properties are not preserved (CORONA ET AL., 2020). The same applies to recycled materials. Therefore, there is a fundamental decision to be made when a product reaches the end of its useful life: Is it possible to restore that product or component to the conditions that enable it to be used for its intended purpose?

At the end of its lifecycle, a product requires a decision regarding the treatment it will undergo as a whole or its individual components. Active disassembly and remanufacturing are a more sustainable production method than the current manufacturing approach (CHIODO & IJOMAH, 2014). Moreover, recycling a part containing different materials will result in lower quality and consequently offer fewer applications than recycling a component made of uniform material (CORONA ET AL., 2020). Conversely, recycling a part hinders the remanufacturing of its smaller constituent components. Hence, decision-making for EOL products merits thorough investigation.

Gerrard & Kandlikar (2007) concluded that the decision-making process for end-of-life vehicles (ELVs) in the EU is currently highly limited. Manufacturers tend to disassemble only the components they are legally required to remove from the vehicle. Subsequently, the remainder of the vehicle is separated into materials for recycling. This separation is often carried out with little precision and employs heavy and imprecise machinery. Producers aim to save time and meet the required levels of recycled material stipulated by law. The quality of recycling or the potential remanufacturing of components is excluded from the scope of decision-making. The existing and future legislation and the current operational practices will be further explored.

Figure 1 illustrates an IDEF0 diagram modelling the ELV recovery process. The arrows at the top of the rectangle represent external influences, while those at the bottom represent resources.

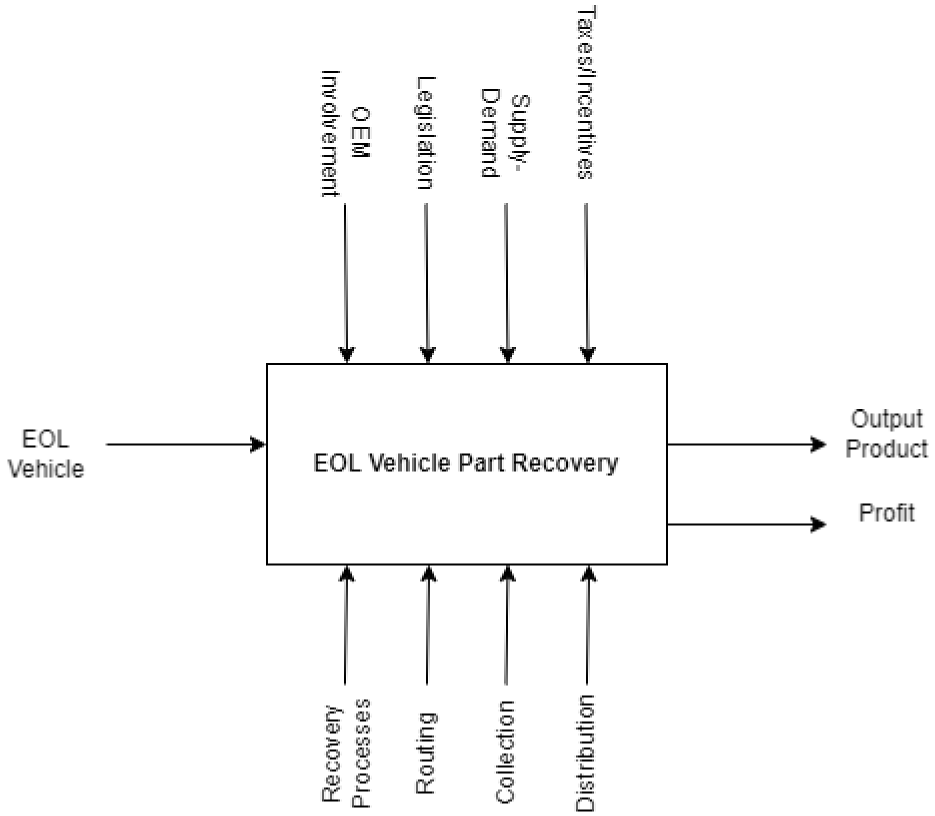

Figure 1. *EOL product recovery IDEF0 adapted from* (Ziout et al., 2014a).

Scaling up the Circular Economy (CE) from front-runners to the mainstream economic players will make a decisive contribution to achieving climate neutrality by 2050 and decoupling economic growth from resource use (EUROPEAN COMMISSION, 2020). The primary motivation behind this thesis is to bring the concept of CE to the automotive sector by exploring a frequently overlooked aspect in this industry: the decision-making processes concerning ELVs.

1.1 Approach

The main objective of this Thesis is the development of a structured evaluation system to decide whether the best option for a vehicle or a vehicle part at the end of its life is to disassemble or scrap it. The system will use Key Performance Indicators (KPIs) to define the vehicle's status to achieve this goal. The result of implementing this system should be sufficient to discern whether disassembling the analysed vehicle or part is the best option.

This thesis aims to develop a system to assess whether the best option for a vehicle, or a part of it, at the end of a life cycle is to disassemble or scrap it. For this purpose, KPIs will be used to define the vehicle’s status.

The development of this thesis aims to address the following Research Questions:

RQ1: What analysis is currently carried out to determine whether a vehicle is disassembled or scrapped?

RQ2: Which KPIs are necessary to decide between disassembling or scrapping the vehicle?

RQ3: What would a system look like that, using the necessary KPIs, would assess whether the best option is to disassemble the vehicle or any of its parts, or to scrap it?

The development of this thesis aims to provide the following Research Contributions:

RC1: Analysis of current methods for decision-making related to disassembling in the automotive industry.

RC2: Review of current KPIs focused on ELV decision-making.

RC3: Development of a framework to help decide whether a vehicle or any of its parts should be disassembled or scrapped.

The following approach has been utilized for this research:

- Acquisition of knowledge in the field of sustainability applied to the automotive sector.
- Familiarisation with the processes currently used for EOL decision-making in the automotive industry.
- Analysis of the KPIs described in the literature applied to EOL decision-making.
- Development of new specific KPIs focused on the decision to disassemble cars.
- Creation of a structured system that brings together the KPIs relevant to the decision to disassemble.
- Application for system validation in a simulated example.

1.2 Systematic Literature Research

For the development of the framework, a systematic literature review has been conducted. It should be noted that not all the documents cited in the thesis are extracted from this review, as a preliminary study was conducted to acquire a sufficient level of knowledge in this field, and some of these studied documents have been cited in this document. Nevertheless, all the documents cited during the development of the DMF were obtained through this systematic literature review.

The boundaries of this systematic literature review are initially defined as follows:

- Search engine: SCOPUS.
- Language: English.
- Search target: Tools or considerations for ELVs decision-making.

The input search terms have been crafted using key elements “End-of-Life,” “assess*,” and “vehicle*.” Subsequently, equivalent terms have been appended to these key elements, as illustrated in Table 1. The terms denoted with "*" at the end are intended to encompass variations with different word endings. For instance, “remanufactur*” prompts the search engine to account for both “remanufacture” and "remanufacturing." When "End of Life" is enclosed in quotation marks, it ensures that the search engine treats it as a single phrase, rather than separate words.

	Main aspects		
	End-of-Life	**Assess***	**Vehicle***
Equivalent aspects	“End of life”	Tool*	Auto*
	EoL	Evaluat*	Car*
	ELV	Framework	
	Remanufactur*	Decision-making	

Table 1. *Search terms used in the systematic literature research.*

The following search was entered into the search box:

End-of-life OR “End of life” OR EoL OR ELV OR remanufactur AND assess* OR tool* OR Evaluat* OR Framework OR decision-making AND vehicle OR auto* OR car**

“OR” command enables search engine to select from equivalent terms, while "AND" command combines chosen aspects.

Excluded subject areas:

Medicine, nursing, psychology, health professions, veterinary, pharmacology, toxicology, and pharmaceutics.

Following this initial search, 171 results were obtained. Titles of all of them were read, and 47 documents unrelated to the research field were excluded.

Abstracts of the remaining 124 articles were then read out. This information was used to classify documents into 3 categories or direct discarding:

- Category A: Main documents for the development of the assessment framework. Documents that show evaluation systems like the one to be developed or study different systems.
- Category B: Documents relevant to the development of the assessment framework. They contain information that could be relevant for the development of the framework.
- Category C: Documents relevant to the writing of the thesis. They give context to the thesis and help discern why each decision is made in the writing of the thesis.

Outcome after the abstracts reading:

- Category A: 24 documents.
- Category B: 30 documents.
- Category C: 23 documents.
- Discarded: 47 documents.

Next step was a skim reading of category B documents. The ones that can be considered as category A were promoted. Irrelevant or inaccessible documents were deleted. Some lines about what each document could contribute to the framework were noted for future use.

After this step:

- 4 documents were promoted to category A.
- 1 cited document was listed as category A.
- 1 document was relegated to category C.
- 10 documents were deleted because they were not accessible.

Documents considered as category A were read next. The less-appropriate documents were re-listed to category B. Some irrelevant or inaccessible documents were deleted. A new list of cited articles of interest was created.

A comprehensive summary document was created for each of the documents considered as category A. After reading the abstracts of interesting papers cited in category A papers, they were classified in each case as A, B, or C or discard.

This was the total sum per category:

- Category A: 20 documents.
- Category B: 21 documents.
- Category C: 24 documents.

Finally, an in-depth study of the documents selected as category A was conducted for the development of the framework. Category B documents were used to support some aspects of the framework. Category C documents were used as context in the writing of this thesis.

2 Fundamental Concepts

This section will define concepts that are fundamental to the understanding of the thesis. Furthermore, relationship between the described terms and how they are currently understood in the automotive industry will be examined.

2.1 Sustainability

As outlined in GEISSDOERFER ET AL. (2017), the term sustainability, derived from the French verb “soutenir” meaning “to hold up or support”, finds its roots in the field of forestry. Its conception is grounded in the principle of silviculture, which emphasizes that the volume of wood harvested should not surpass the volume that regenerates. Subsequently, the concept was extended to the realm of ecology, where it became a principle of acknowledging and preserving nature's capacity for self-regeneration. It is from this context that the contemporary definition of sustainability emerged, encompassing the notion of being “capable of being maintained at a certain rate or level.”

Sustainability, which protects against the dramatic depletion of natural resources and preserves them for long-term application, relies heavily on the products and materials loop, which is inevitable in the case of a traditional linear economic system, where products and materials are dumped as waste after usage (MOLLA ET AL., 2022). In contrast to this conventional linear economic model, there is CE.

2.2 Circular Economy

CE is a production and consumption model involving sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended. These can be productively used again and again, thereby creating further value (European Parliament, 2023).

Figure 2 shows some of the strategies favouring the CE in hierarchical order.

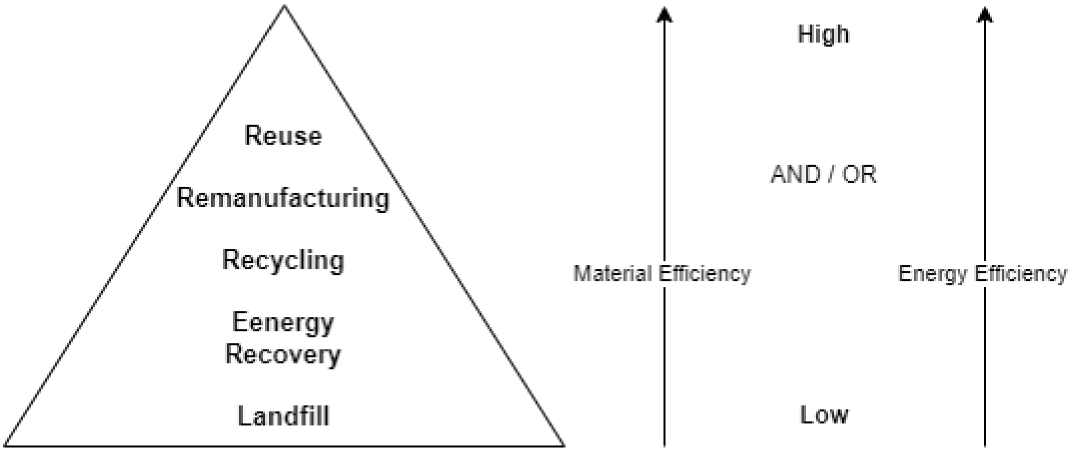

Figure 2. *Theoretical recovery hierarchy (GO ET AL., 2011). Adapted.*

2.2.1 Circular Economy Legislation in the Automotive Industry

Strategies that favour CE can be implemented at any stage of a vehicle's lifecycle. A vehicle that is no longer deemed useful in one country can be adapted to comply with the regulations of another, allowing it to be sold in a market where its useful life can be extended. For instance, a vehicle that remains unsold in a right-hand driving country can be modified for left-hand driving, thus prolonging its utility. Another example involves a fully functional vehicle part from a vehicle that has reached the end of its useful life. This component can be relocated to another vehicle, extending its lifespan. These examples illustrate the application of CE strategies throughout a vehicle's useful life.

Application of CE strategies at the end of a vehicle's lifespan varies depending on the legislation of each country and the available resources. Nonetheless, this part of the vehicles' lifecycle operates remarkably similar across countries with the most advanced legislation in this regard. While this thesis does not focus on any specific region, it aims to enhance the methodology based on countries where legislation concerning vehicle circularity is more stringent.

The EU published a proposal for a regulation of the European Parliament and of the Council on circularity requirements for vehicle design and management of ELVs on July 13th, 2023 (EUROPEAN COMMISSION, 2023b). This proposal aims to facilitate the transition of the automotive sector to the CE, at all stages of the vehicle - from design to final treatment at EOL. The proposal is based on an evaluation of current legislation, which consists of two directives (Directive 2000/53/EC and Directive 2005/64/EC) on the type-approval of motor vehicles regarding their reusability, recyclability, and recoverability.

In the year 2000, the ELV Directive was established as the first harmonized framework within the EU (EUROPEAN PARLIAMENT, 2000), aiming to guarantee the ecologically responsible treatment of vehicles that have reached the end of their operational life and are categorized as waste. This directive outlines regulations pertaining to the gathering and environmentally friendly detoxification of ELVs, imposes limitations on hazardous substances in new vehicles, and establishes objectives concerning the reuse and recycling rate (85%) as well as the reuse and recovery rate (95%) – both of which are calculated based on the average weight of ELVs per vehicle and annually. Since its inception, this legislation has remained essentially unaltered.

The 3R type-approval Directive, sanctioned in 2005 (EUROPEAN COMMISSION, 2023a) forges a strong connection between the stipulations of the ELV Directive and the design prerequisites concerning reusability, recyclability, and recoverability within the type-approval procedure for various vehicle types. Notably, the 3R type-approval Directive mandates that vehicles must be designed with a recyclability and reusability rate of 85%, along with a recoverability rate of 95%. Correspondingly, the ELV Directive prescribes analogous objectives for Member States concerning vehicle reusability, recoverability, and recyclability.

The proposed regulation cancels out the 3R type-approval and ELV Directives and puts a single legal framework in place instead. Its main goal is to update the existing EU laws and improve how the EU single market operates, all while lessening the harmful environmental effects connected to how vehicles are designed, made, used, and disposed of. Additionally, it aims to support the sustainability of the automotive and recycling sectors.

The proposal is based on an impact assessment, published together with the proposal. The impact assessment identified four problem areas to tackle at the EU level:

1. There is a lack of integration of circularity in vehicle design and production leading to high dependencies on primary raw materials.
2. The quality of treatment of vehicles at the end of their life is suboptimal compared to the potential to retain more environmental and economic value.
3. Important share of ‘missing vehicles’ subject to the ELV Directive is not collected to be treated under proper environmental conditions. A large volume of non-roadworthy and polluting used vehicles are exported from the EU annually.
4. There is unexploited circularity potential of vehicles currently outside the scope of the ELV.

The development of this thesis aims to contribute to the first two issues listed.

2.2.2 Circular Economy in the Contemporary Automotive Industry

Application of CE concepts to the automotive industry varies significantly depending on the country's legislation being analysed. This section aims to analyse the implementation of the CE in the current automotive industry, focusing on examining the procedures in countries with more stringent regulations in this regard. These countries represent, in a better way, the best practices in the field of ELVs in the industry today. In addition, some of the most innovative applications of this concept by leading Original Equipment Manufacturers (OEMs) have also been studied.

SATO ET AL. (2019) describes the process vehicles follow at the end of their useful life in Japan. Initially, the discarded vehicles are sent to dismantling companies. Next, their fluids, batteries, tires, and airbags are removed as a preventive measure. Subsequently, based on the vehicle model and considering the market demand, specific automotive parts are selected and extracted to be resold as second-hand spare parts. At the procedure stage, other parts are separated to be recycled as alternative raw materials. The remaining dismantled vehicles are pressed and sent to shredding companies.

Figure 4 shows the path EVLs, and their components follow and the processes they undergo.

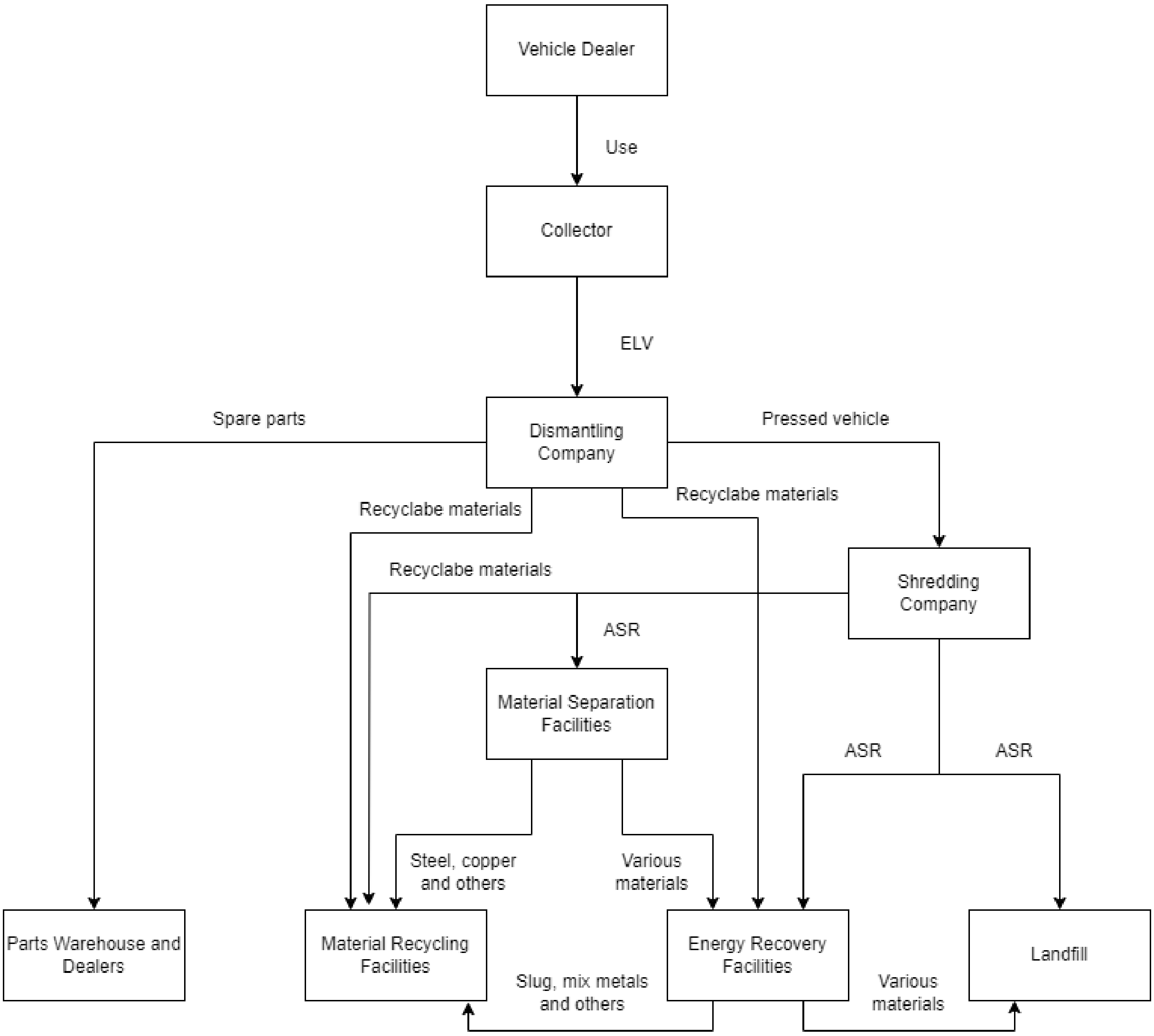

Figure 3. *Current vehicle life cycle and recycling system (SATO ET AL., 2019). Adapted.*

The process followed by disassembled and crushed vehicles upon reaching shredding companies is detailed in Rosa & Terzi (2018). The scraps are separated by exploiting their physical characteristics (e.g., density, weight, and magnetism) to obtain uniform groups of materials. In general, ferrous metals (about 65% of the average mass) are directly reintroduced into the automotive supply chain (as input material for foundries). Non-metals (generally named Automotive Shredder Residue (ASR) and constituting about 25% of the average mass) are currently landfilled or used as fuel for energy generation. Finally, non-ferrous metals (5% of the average mass) – depending on the specific treatment plant’s set up parameters – becomes impurities of both the ferrous and non-metal fractions.

Figure 4 shows a diagram of the shredding companies' procedure.

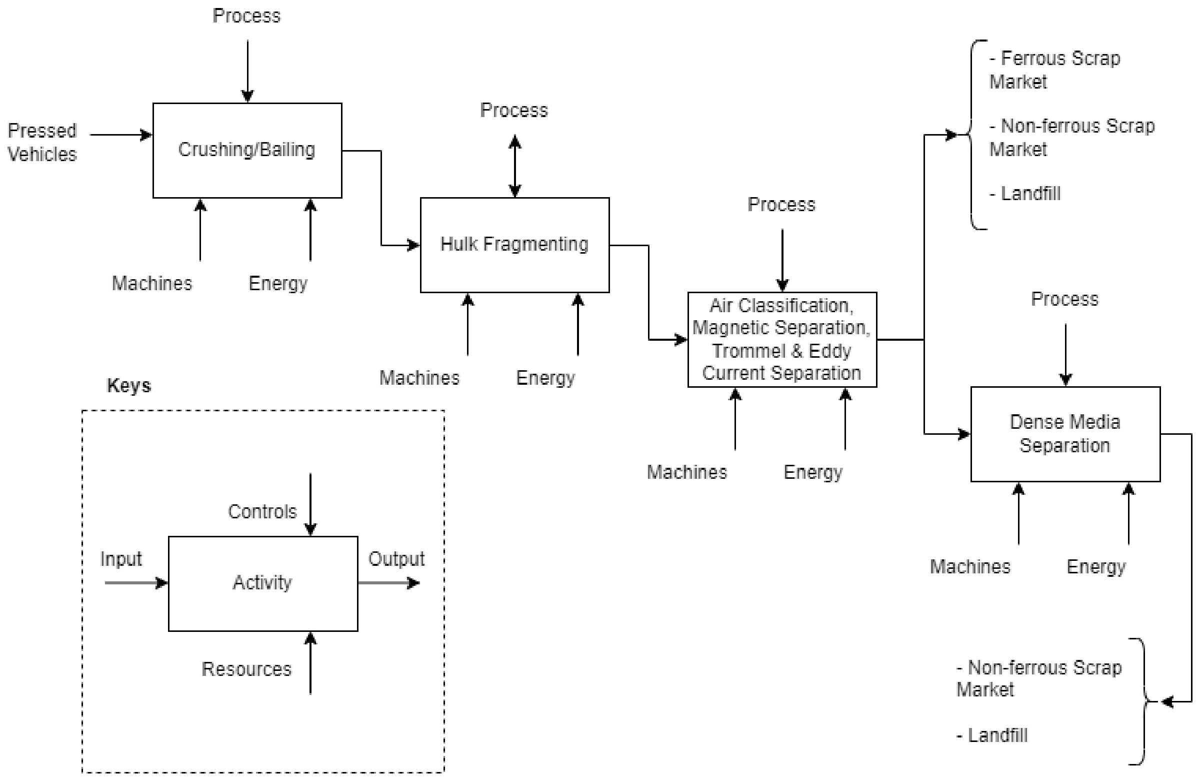

***Figure 4.** Shredding companies' procedure (ROSA & TERZI, 2018). Adapted.*

Ethical and moral responsibility, current legislation, and the direct economic benefit of CE are not sufficient reasons for OEMs of vehicles to strengthen how they deal with the ELV they receive. SEITZ (2007) found that other motivations could lead OEMs to explore previously uncharted strategies such as remanufacturing. These motivations include ensuring a stable supply of components, reducing dependency on parts suppliers to some extent, controlling the quality of parts for sale, enhancing the brand's image, or satisfying customers by selling parts separately.

Alternative option is for the EVLs to return to their OEMs. Figure 5 illustrates the path that cars managed by BMW Group follow at the end of their service life.

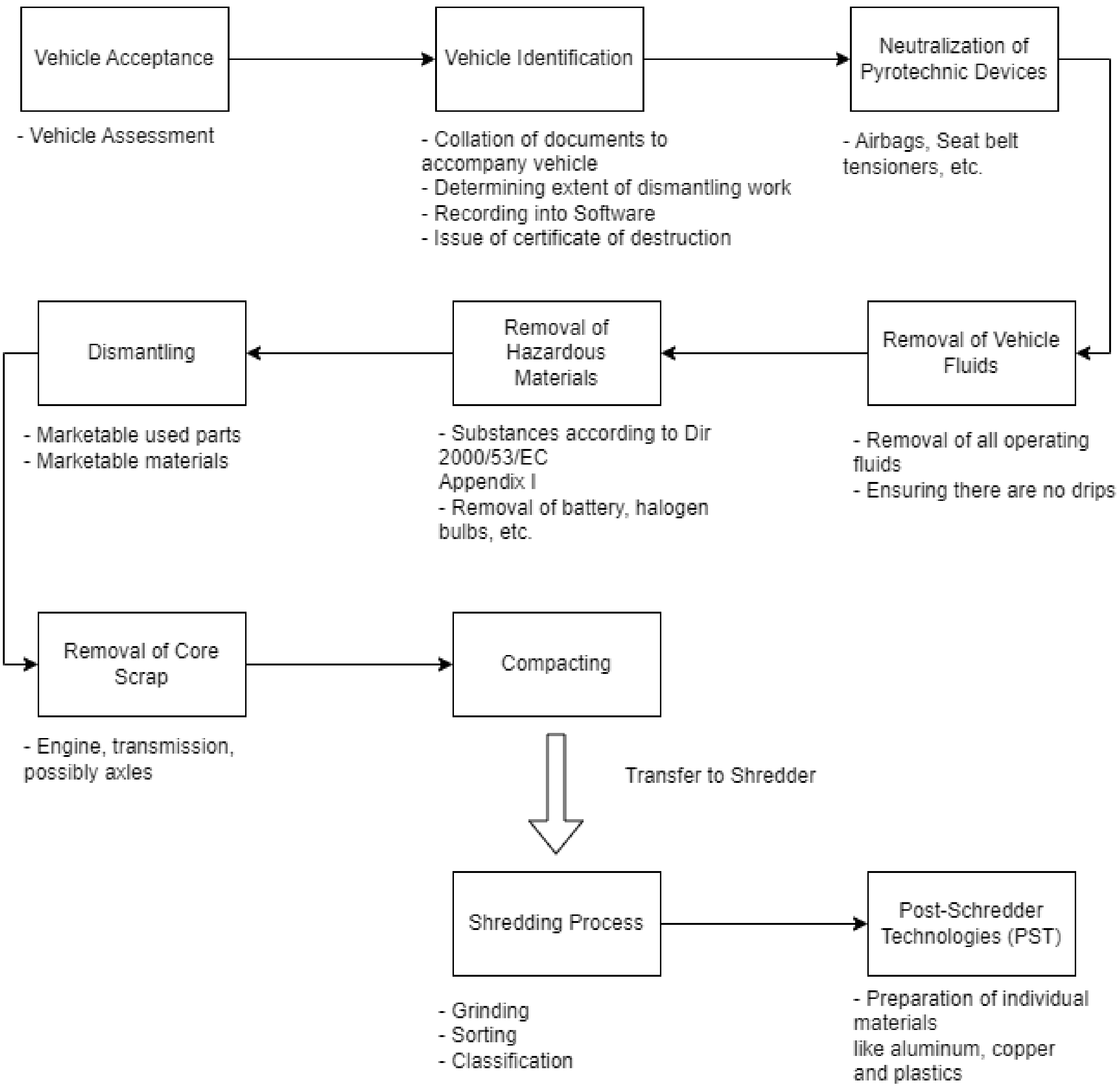

Figure 5. *BMW Group ELVs' recovery (BMWGROUP.COM, 2009). Adapted.*

The marketable parts that BMW Group recovers are not assembled into new vehicles or sold to the public by the brand. Specialized companies in selling these second-hand parts are responsible for ensuring that these components return to vehicles in use.

OEMs can be responsible or not of the second-hands parts' selling. Peugeot offers its customers a range of second-hand parts, distinguishing between refurbished parts, reused parts, and repaired parts (PEUGEOT.COM, 2021)

Peugeot classifies these types of parts as follows:

- Renovated parts: These parts have been refurbished according to the manufacturer's specifications. Most of these parts are major mechanical components: engines, gearboxes, clutches, but also electronic parts.
- Reused parts: These parts have been recovered from ELVs and their quality is "standard" or "premium".
- Repaired parts: Some parts of the vehicle, such as the audio system or the gearbox can be repaired. An approved partner takes care of repairing them to full working order.

Another example of CE applied within the automotive industry is Design for Remanufacturing (DfRem). DfRem is a type of product design oriented to enhance remanufacturing. The producer needs to consider the remanufacturing performance at the design stage of the original product and specify specific design indicators and requirements so that the final scrap is in a good remanufacturing state, which involves easy collection, easy disassembly, easy update, and easy evaluation. DfRem occurs during the design phase of a new product but is significantly effective during the remanufacturing phase (NIU ET AL., 2019).

An example of the application of DfRem in the automotive industry is the use of modular engines, as seen in brands like Volvo and BMW, and described by NIU ET AL., (2019). Modular engines have interchangeable components that share certain characteristics, such as the same caliber or cylinder spacing. BMW, for instance, ensures that among engines using the same type of fuel (whether gasoline or diesel), more than 60% of the components are shared, and between 30% to 40% of the components are shared with engines designed for a different fuel type. This practice not only simplifies the technical challenges of remanufacturing but also significantly enhances the economic margins of the operation. Figure 6 shows the modular engine design of a Volvo car.

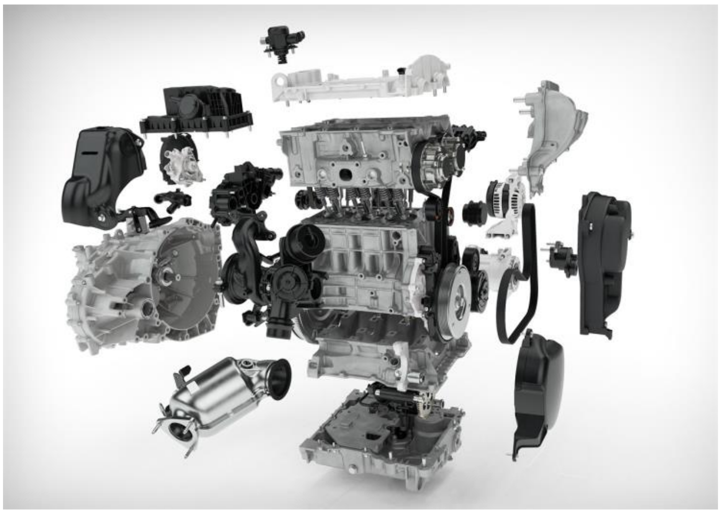

Figure 6. *Volvo's Drive-E 3-cylinder Petrol - modular design (MEDIA.VOLVOCARS.COM, 2018).*

3 Understanding Need for Action

For the development of this thesis, a visit was made to the Recycling and Disassembly Centre of BMW Group in Unterschleißheim, Germany.

Although significant conclusions about the decision-making methods employed by the brand could not be drawn, it was possible to observe workers retrieve specific parts from the vehicles. After removing the components and fluids the law requires to be disposed of; the workers remove the sought-after components, which vary depending on the vehicle. These parts are sold to companies specializing in reselling second-hand vehicle parts.

This centre receives vehicles used for testing, many of which may be damaged due to these tests. For safety reasons, the brand does not use any of these vehicles to resell second-hand parts, no matter how minor the damage may be, even if a significant portion of the parts are entirely intact. The reselling parts are obtained from vehicles returned at the end of their useful life.

The sought-after parts are removed by the workers in one of the centre’s warehouses. Upon arrival to the centre, all vehicles are identified with a QR, and registered in internal software. Through this QR code, the workers can subsequently access the vehicle's history they are working with. The workers evaluate the removed components using a catalogue that includes assessment criteria. Finally, the workers classify the components as A, B, or C based on their condition, with A indicating the best condition, B representing an intermediate state, and C denoting the worst condition. With the sale of these parts to resellers, the BMW Group's parts recovery plan is completed. All brands are legally obligated to have such a plan in place (EUROPEAN PARLIAMENT, 2000).

Decisions regarding the components of vehicles at the end of their useful life rely on the expertise of the workers who remove them. It can be concluded that the decision-making process regarding EOL components of vehicles is often overlooked when these vehicles are returned to their OEMs. Nevertheless, some authors have developed decision-making methods for EOL products (whether they are vehicles or not) that are more complex and could potentially be integrated into this part of the process in the future.

4 End-of-life Decision-making State of the Art

The EOL decision-making methods found in literature can be classified into five categories (ZIOUT ET AL., 2014b):

- Category 1: Exhaustive enumeration methods. These methods have a limited number of solutions which are generated by adding and/or subtracting values of selected (usually unjustified) factors.
- Category 2: Mathematical optimization methods. Decision of selecting the best recovery option for a product or its subassemblies is formulated as an optimization problem; The decision of these methods is completely dependent on cost/benefit data which varies by time and could be not available at earlier stage of product development; this makes the practical use of such methods questionable due to the significant efforts needed to keep real time data.
- Category 3: Multi-criteria methods. Decision Support models are used to assign each component in a product to possible EOL options ranked from most to least preferred option. These methods have advantages on the above ones due to its technical aspects and structure; it can take quantitative and qualitative data at the same time, inclusion of decision maker preferences, and ranking options instead of selecting a single one. Multicriteria methods suit the nature of recovery problem in the sense of inclusiveness and comprehensiveness; a reliable and realistic decision should be based on a holistic approach that considers all aspect of EOL recovery option selection.
- Category 4: Clustering methods. Clustering methods use the computational power and artificial intelligence of computers to cluster a population of products into clusters (groups), each group has products which share similar characteristics. The clusters represent recovery options, products fit in one cluster have the same recovery option. The output of clustering methods depends on the quality of data set used in the learning process; same clustering technique could assign a product to different recovery options if the learning data set is different.
- Category 5: Empirical methods. The decision on appropriate recovery option is made based on knowledge and experience extracted from analysing successful cases of product recovery.

This thesis employs Multi-criteria Decision-making (MCDM) methods (Category 3), which can blend qualitative and quantitative criteria on one hand and technical, environmental, and economic criteria on the other.

Many of the MCDM methods found in the literature are preceded by the term "Fuzzy." Fuzzy analysis represents a method for solving problems which are related to uncertainty and vagueness; it is used in multiple areas, such as engineering and has applications in decision making problems, planning and production (COROIU, 2015).

Among the documents analysed, Analytic Hierarchy Process (AHP) is the most widely used approach for weights calculation of MCDM methods' different criteria. This method is employed in this thesis' framework and will be described further on.

A used extension of this approach is the Analytic Network Process (ANP). As described by GOVINDAN ET AL. (2016), this version particularity is the interdependencies evaluation between different clusters. The fundamental challenge of this approach lies in the difficulty of assessing the interdependencies between various criteria as the number of criteria (and hence interdependencies) grows. To address this, supporting methods are often employed. The most common ones are Interpretive Structural Modelling (ISM) and Decision-making Trial and Evaluation Laboratory (DEMATEL), which are also frequently applied separately in decision-making processes. ISM is a computer-aided method for developing graphical representations of system composition and structure (WATSON, 1978). DEMATEL approach is followed to develop the cause-and-effect relationship among the criteria and identifying the influential factors with the highest impact during the decision-making process (SINGHAL ET AL., 2018).

Similarly, mathematical optimization methods (Category 2) have been considered for the economic evaluation. However, conducting a realistic economic feasibility study for each strategy on every component would require highly detailed data on the components and applicable strategies. Some of these methods found in the literature include factors such as disassembly time, labour and machinery costs, and probabilistic variables related to the likelihood of successfully recovering a part after disassembly. Indeed, even in those cases, certain assumptions must be made, such as estimating a fixed time required to disassemble a component or incorporating miscellaneous costs that may not be fully known (PHULUWA ET AL., 2021).

5 Key Performance Indicators Analysis

Key Performance Indicators (KPIs) are management techniques employed to enable efficient and effective business monitoring (GRAHAM ET AL., 2015a). KPIs have been used to assess a company's overall performance, with the aim of collecting specific data that evaluates whether the processes carried out by the company are optimal or not (GRAHAM ET AL., 2015a). In the case of this framework, KPIs serve the purpose of evaluating whether a specific recovery strategy applied to a specific vehicle component is optimal. This presents a challenge, as KPIs from literature will need to be adapted to this thesis' case, and new KPIs will need to be formulated accordingly. This section presents the analysis conducted on the KPIs found in the literature and the extent they can be adapted to the case study.

The key strategic factors that have the most influence on remanufacturing in the automotive industry are strategic product planning, design for remanufacturing, plant location, production systems, physical distribution, and cooperation among remanufacturing stakeholders (SUBRAMONIAM ET AL., 2009). These factors also influence the individual component-level decision-making process. For example, if a part has a well-designed structure for remanufacturing, technically applying this technique to an individual component will be simpler. This will influence how the most favourable strategy is selected.

Table 2 analyses interesting KPIs found in literature related to components' second life. Third column shows the examination carried out to determine whether the KPI evaluates a technical, environmental, economic aspect, or a combination of these aspects. Fourth column shows a classification of KPIs into quantitative or qualitative.

Last row shows an evaluation conducted regarding how applicable these KPIs are to the decision-making process studied in this thesis. KPIs with high adaptability are directly incorporated into the framework. Those rated as moderate have been modified to create new KPIs. The ones classified as low have served as a foundation for the creation or modification of other KPIs.

KPI	KPI description/question	Aspect assessed	Type	Adaptability to the framework
Product Margin	Margin on each product remanufactured, expressed as a percentage	Economic	Quantitative	High

KPI	KPI description/question	Aspect assessed	Type	Adaptability to the framework
Cycle Time	Total time from the beginning to the end of a process; usually the whole remanufacturing process	Technical, Economic	Quantitative	Low
Workload	Workload involved in producing the equivalent of one unit of product	Technical, Economic	Quantitative	Low
Materials Used	Amount of material by weight or volume used in remanufacturing, including materials purchased from external suppliers or from internal sources.	Technical, Economic	Quantitative	Medium
Recycled Material Used	Percentage of recycled material used in remanufacturing process.	Environmental	Quantitative	High
Direct Energy Consumption	Total amount of energy used, derived from primary sources	Environmental	Quantitative	High
Total Green House Gas Emission	Total amount of Green House Gas emitted.	Environmental	Quantitative	High
New Components Cost	Cost of new components used during the remanufacturing process.	Economic	Quantitative	Medium
Component Salvage Rate	Percentage of reused components/subassemblies in a product.	Economic, Environmental	Quantitative	High
Design for Remanufacturing	Does a component's design, with respect to ease of (re)manufacture,	Technical	Qualitative	Medium

KPI	KPI description/question	Aspect assessed	Type	Adaptability to the framework
	influence the decision to remanufacture?			
Disposal Cost	Level of influence of the disposal cost in the decision	Economic	Qualitative	Low
Green Perception	Level of green perception of the strategy applied to a component	Environmental	Qualitative	Low
Ecotoxicity	Level of influence of the material's toxicity, concerning environment, for in the decision	Environmental	Qualitative	Medium
Human toxicity	Level of influence of the material's toxicity, concerning humans, for in the decision	Environmental	Qualitative	High
Resource Extraction Concerns	Level of concern on material's extraction, because of depletion or difficulty	Environmental, Technical	Qualitative	Medium

Table 2. *KPIs' analysis breakdown from* GRAHAM ET AL (2015B)*,* PILLAIN ET AL. (2017)*,* SUBRAMONIAM ET AL. (2013)*, and* YANG ET AL. (2016).

6 End-of-life Decision-making Framework

As a preliminary clarification, when the word “part" is mentioned, it refers to an element that can be disassembled, usually made of homogeneous material. When the term "component" is used, it refers to a set of parts assembled that can be separated as a whole from the rest of the vehicle.

The main goal of this Decision-making Framework (DMF) is to compare what it entails to disassemble a component and thus apply a treatment to each part separately to not doing so. For this purpose, analyse what the best option would be for each part. This way, the best option is determined for each part and if it is worth disassembling it is decided for the component.

This DMF is designed for systematic part evaluation. In other words, it serves as an operational DMF. Operational decisions are those encountered on a day-to-day basis (GOODALL ET AL., 2014). In the remanufacturability or recyclability context, this type of decision primarily focuses on evaluating individual products and parts. Within a disassembly facility, this decision is incorporated into the process through product inspections. The objective of an inspection is to filter out products and parts that are unsuitable for remanufacturing or recycling, ensuring that resources are not wasted on unnecessary measures.

On the other hand, this DMF is not solely reliant on the technical inspection of parts but also on the appropriateness of the strategy at a higher level, based on attributes independent of the degradation state of the part. These tactical decisions are based on specific types and models of parts, rather than individual components (GOODALL ET AL., 2014). For instance, if a specific treatment does not exist or is not suitable for a type of component, that decision is not dependent on the individual part.

This DMF combines features of both tactical and operational decision-making methods. This becomes particularly significant given the gap in the literature concerning operational decision-making methods that integrate an environmental analysis of the component.

The framework is designed for conducting a non-destructive disassembly. Destructive disassembly entails the risk of parts breaking during the disassembly process, whereas non-destructive disassembly ensures that the parts are separated from the ELV while preserving their integrity to the maximum extent possible (TIAN & CHEN, 2016).

Although the decision to opt for non-destructive disassembly may seem logical, it is less common compared to the choice of destructive disassembly. Currently, there are limited mechanisms for remanufacturing parts by OEMs, and recycling does not necessitate careful disassembly (TIAN & CHEN, 2016). Some authors even define destructive disassembly as "material separation for recycling" (ANTHONY & CHEUNG, 2017), implying that it is not suitable for higher-level recovery strategies. Destructive disassembly also hampers recycling, as carefully separated components yield higher-quality recycled materials with a significantly broader range of applications.

Within the method, when analysed by part, the main goal is to find the strategy that best suits each part. The three options that the DMF will assess are remanufacture, recycle, and dispose of.

There are diverse definitions regarding the paths a product or part can take at the end of its useful life. These definitions vary among authors, making it crucial to specify what is meant by "remanufacture," "recycling," and "scrap." In this case, the DMF adopts the definitions provided in LOW ET AL. (1997):

1. Remanufacture: The product is recovered and restored to its original condition (both function and cosmetics). This includes the reuse of components and materials.
2. Recycling: The product is disassembled to recover the materials and perhaps components.
3. Scrap: Product and or its elements go to landfill or incineration.

The other two options offered by the author, namely "resale" and "upgrade," are excluded from the framework. "Reseal" is defined as "the existing product recovering and selling, with minimum intervention, to another customer requiring a similar product function. This may be in the same geographical location or may be in another more distant second market." "Upgrade" is defined as "improving existing product's functionality on the customer premises."

Resale is discarded due to the difficulty of distinguishing it from remanufacturing. Remanufacturing implies that the component returns to its original condition, which is not the case with the resale strategy. Additionally, one of the main goals of this thesis is enhancing circularity of the vehicles' lifecycle by making it closed loop, making it preferable for components to return to the vehicles they were designed for.

The evaluation of each component will depend on three criteria: technical suitability, environmental performance, and economic performance. Each criterion is further broken down into several attributes that depend on the strategy being evaluated and will be presented later in the text. These attributes can be either qualitative or quantitative in nature.

The steps followed by the method are as follows:

1. The suitability of the component for remanufacturing is evaluated using a Fuzzy MCDM method. The weights of the criteria and attributes are designated beforehand by applying an AHP.

2. The suitability of the component for recycling is evaluated using the same methods but different attributes.
3. The option with the highest suitability index for the component is chosen. If neither of the two treatments scores more than a 4 (the limit considered for a non-suitable treatment), it will be considered that the component should be disposed of.
4. Once the treatment that best suits the component is chosen, the sum of the costs or benefits of disassembling the part is calculated.

If a component is legally required to undergo a specific treatment, it will not be considered within the method, and it will follow the mandatory treatment as required by law. In the event of a tie between the remanufacturing and recycling strategies, the remanufacturing option will always be preferred, as it is the strategy that returns the components to the vehicle closing the loop.

Figure 7 shows a diagram of the process followed by the DMF.

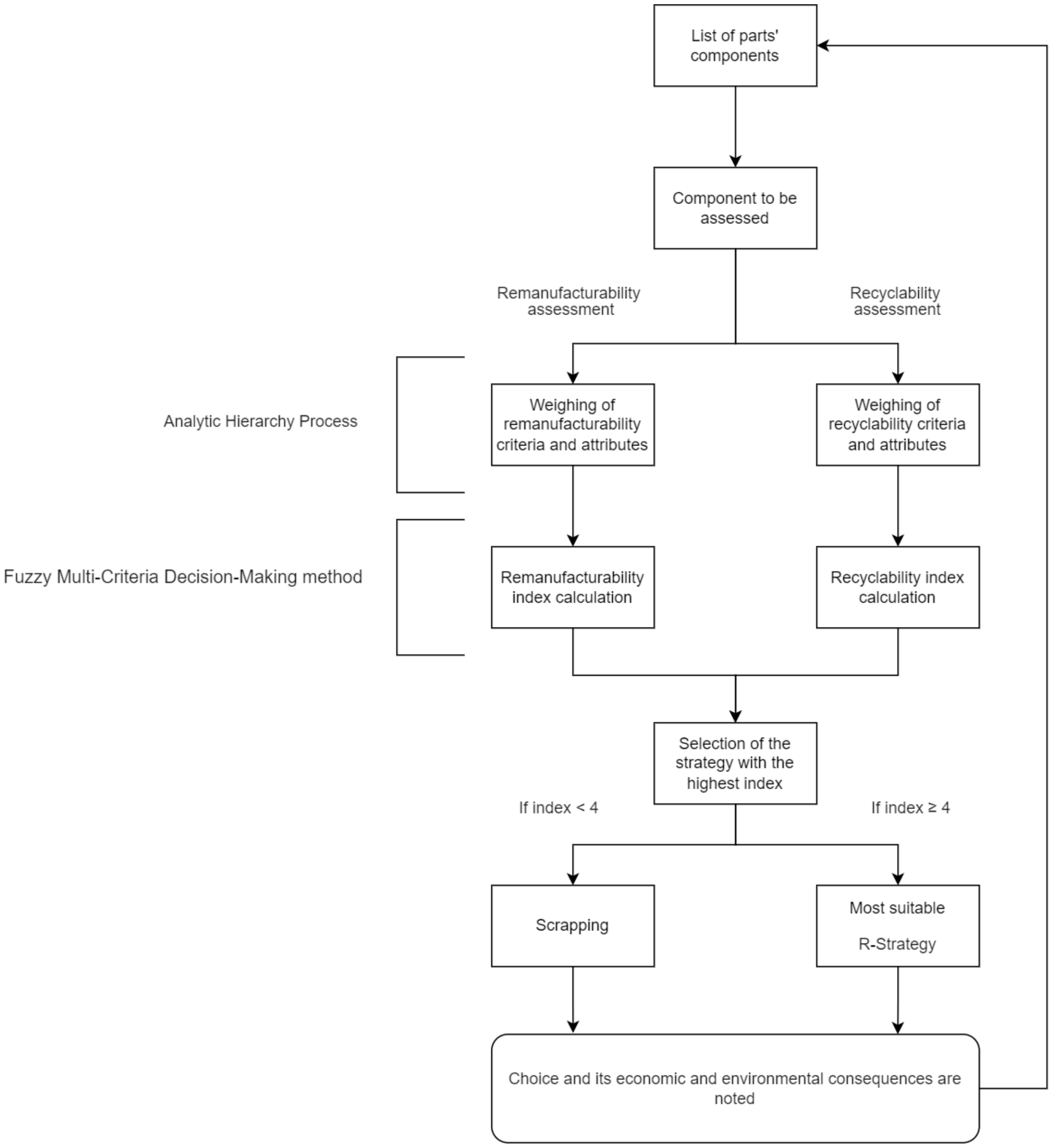

Figure 7. *DMF illustrative overview.*

6.1 Analytic Hierarchy Process

As described by SUBRAMONIAM ET AL. (2013), AHP is a theory and measurement process using pairwise comparisons based on expert judgments to derive priority scales. These scales help researchers measure intangibles in relative terms. The comparisons are made using a scale of judgments that represents how much one element dominates another with respect to a given attribute. Pairwise comparisons of the attributes considered can only be made subjectively, so the accuracy of the results depends on the user's experience/knowledge of the subject matter.

Judgments can be inconsistent. Therefore, AHP is effective by design in measuring inconsistencies and improving judgments, where possible, to obtain greater consistency.

Within this DMF, the AHP will be used as a method to compare attributes within a criterion and criteria against each other. In this way, the attributes of the same criterion will be assigned a weighting according to their preponderance over the other attributes that make up the criterion, as determined by expert opinions. Similarly, the criteria will be compared among themselves, and their weights will be established through expert judgments.

An unlimited number of experts can be asked in pair-wise comparisons of criteria or attributes. Surveying a large number of experts can lead to a better understanding of the industry and, consequently, yield more compelling results for the DMF. The averages of the approximate comparison results, rounded to the nearest integer, will be the values entered in the pairwise comparison matrices.

The question that the experts will answer through the AHP method is: "How important is the consideration of this attribute or criterion compared to this other in evaluating the remanufacturability or recyclability of this component?".

An example of such a question could be: “How important is the consideration of the “Green House Gas Emission” compared to the “Direct Energy Consumption” when evaluating the remanufacturability of the door assembly?”.

AHP is based on the reciprocal axiom, that requires that if $P_C(E_A, E_B)$ is a paired comparison of elements *A* and *B* with respect to their parent, element *C*, representing how many times more the element *A* possesses a property than does element *B*, then $P_C(E_A, E_B) = 1/P_C(E_B, E_A)$. For example, if *A* is 5 times more important than *B*, then *B* is one fifth as important as *A*. In the case of this DMF, if Material Scarcity (*A*) is considered to be six times more important than Toxicity (*B*) when evaluating the Recyclability (*C*) of a component, then Toxicity (*B*) is one-sixth as important as Material Scarcity (*A*). These comparisons constitute the so-called importance matrices.

Importance matrices are considered the core of AHP model due to the following two reasons (ZIOUT ET AL., 2014b):

1. The capability of considering different decision makers preference using the same method. EOL product recovery problem has many stakeholders; each has his own preferences and perspectives with different objectives which sometimes conflict with other stakeholders’ objectives. The importance matrices in AHP method give this capability.

2. Systematic way of translating subjective and qualitative assessment into quantitative assessment. Importance matrix is formed by conducting pairwise comparison between a set of criteria. Comparison is made between elements in a level with respect to their ancestor in a higher level. The purpose of importance matrices is to find the weight of each element in the overall hierarchy. A set of criteria or attribute weights is called an eigenvector.

The valuation scales used in the example are those recommended by SUBRAMONIAM ET AL. (2013) where 1 is equal importance, 3 is moderate importance, 5 is strong importance, 7 is very strong or demonstrated importance, and 9 is extreme importance. Even numbered values will fall in between the above importance levels like a scale of 6 representing between strong and very strong. Table 3 shows an importance matrix obtained during the DFM validation.

	GHGE	DEC	TOX	MS	RMU
GHGE	1	1	3	1	1
DEC	1	1	4	2	1
TOX	0.33	0.25	1	1	1
MS	1	0.50	1	1	2
RMU	1	1	1	0.50	1
Sum	4.33	3.75	10	5.50	6

***Table 3.** Pairwise comparison matrix obtained during the DMF validation.*

The next step is the normalization of the columns to make them sum up to 1. This is achieved by dividing the weight of each value in the column by the sum of all the values included in that column. Table 4 shows Table's 3 normalization.

	GHGE	DEC	TOX	MS	RMU
GHGE	0.23	0.27	0.30	0.18	0.17
DEC	0.23	0.27	0.40	0.36	0.17
TOX	0.08	0.07	0.10	0.18	0.17
MS	0.23	0.13	0.10	0.18	0.33

	GHGE	DEC	TOX	MS	RMU
RMU	0.23	0.27	0.10	0.09	0.17
Sum	1	1	1	1	1

Table 4. *Normalized matrix obtained during the DMF validation.*

Obtaining the eigenvector is the goal of applying the AHP to the criteria's attributes or R-Strategy's criteria. To obtain the eigenvector, which in this case can be called the "Weight" vector or W, the average of the weights in each row is taken.

$$W = \frac{1}{5} \times \begin{bmatrix} 1.15 \\ 1.43 \\ 0.59 \\ 0.98 \\ 0.86 \end{bmatrix} = \begin{bmatrix} 0.23 \\ 0.29 \\ 0.12 \\ 0.20 \\ 0.17 \end{bmatrix}$$

This vector is the goal of applying the AHP to the KPIs of criteria or the criteria of an R-Strategy. The relative weights contained in these vectors will be subsequently used for the application of the Fuzzy MCDM method.

The final step involves the calculation of a Consistency Ratio (CR) to measure how consistent the judgments were relative to large samples of purely random judgments. If the CR is much more than 0.1 (or 10%) the judgments are untrustworthy because they are too close to randomness and the exercise is valueless or must be repeated (SUBRAMONIAM ET AL., 2013).

The Consistency Index (CI) and CR for a pairwise comparison matrix is calculated as

$$CI = \frac{(\lambda_{max} - n)}{(n - 1)} \quad (1)$$

Where n is the number of criteria or attributes compared in the pair-wise comparison matrix and λ_{max} the inner product of the column sum row and the eigenvector, matrix W.

In this case, $\lambda_{max} = 5.35$.

$$CI = \frac{(\lambda_{max} - n)}{(n - 1)} = \frac{(5.35 - 5)}{(5 - 1)} = 0.09$$

The CR is calculated by dividing the CI by the Random Inconsistency (RI) value that corresponds to n.

$$CR = \frac{CI}{CR} \quad (2)$$

The RI tables are available in most AHP and ANP reference books and are presented in Table 5.

$$CR = \frac{0.09}{1.12} = 0.08$$

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

Table 5. *RI for each number of compared elements (SUBRAMONIAM ET AL., 2013).*

For a pair-wise comparison matrix to be consistent, CR should be < 0.10. Since the value of CR is less than the threshold value, matrices are consistent, and the process does not have to be repeated.

6.2 Fuzzy Multi-criteria Decision-making

In accordance with KAYA ET AL. (2019), MCDM is a concept which enables to select the most appropriate one among predetermined alternatives by evaluating them in terms of many criteria. MCDM methods, classified as conventional and fuzzy, are effectively used to rank alternatives. The conventional MCDM methods are seen inadequate to handle uncertainty in linguistic terms. Hence, it is proposed to apply MCDM methods with the fuzzy sets to cope with vagueness in a decision-making process.

In the case of this DMF, experts or formulas will evaluate, on a scale from 1 to 10, the suitability of a component for remanufacturing or recycling, considering a specific attribute. This step will be carried out for each attribute. The grading system operates as follows: a score between 8 and 10 indicates "extremely remanufacturable or recyclable," a score between 6 and 8 signifies "remanufacturable or recyclable," a score between 4 and 6 denotes "generally remanufacturable or recyclable," and a score between 1 and 4 indicates "not remanufacturable or recyclable”.

The value 0 is reserved for experts or formulas to unequivocally indicate that a component cannot adopt a strategy due to excessive economic, environmental, or technical drawbacks. In the case of qualitative KPIs, if all experts assign a score of 0 to a particular strategy considering an attribute, the evaluated strategy will be disregarded for that component. Similarly, if the formula yields a score of 0 in the evaluation concerning a quantitative attribute, the evaluated strategy will be dismissed.

The possible number of experts consulted for each qualitative attribute is unlimited in this method. Since this DMF is intended for everyday decision-making, it the same operators who disassemble the component must be capable of evaluating its qualitative attributes.

In the case of quantitative attributes, each attribute is evaluated through different formulas, resulting in a value. The range within which this value falls will determine the score obtained by the component based on that attribute for that strategy. All formulas and the correspondences between values and scores will be presented further on.

Tables 6 and 7 show criteria and attributes considered.

Remanufacturability Criteria	**Remanufacturability Attributes**	**Type**
Technical Suitability	Ease of Remanufacturing	Qualitative
Environmental Performance	Green House Gas Emission	Quantitative ($\mathrm{CO_2eq./kg}$)
	Direct Energy Consumption	Quantitative (kWh/kg)
	Toxicity during Remanufacturing	Qualitative
	Reamanufacturing Material Scarcity	Qualitative
	Recycled Material Used	Quantitative (%)
Economic Performance	Component Value Ratio	Quantitative (%)

Table 6. *Criteria and attributes for the remanufacturability assessment.*

Recyclability Criteria	**Reciclability Attributes**	**Type**
Technical Suitability	Ease of Recycling	Qualitative
	Quality of Recycling	Qualitative

Recyclability Criteria	Reciclability Attributes	Type
Environmental Performance	Green House Gas Emission	Quantitative (kg CO_2eq./kg)
	Direct Energy Consumption	Quantitative (kWh/kg)
	Toxicity during Recycling	Qualitative
	Recycling Material Scarcity	Qualitative
Economic Performance	Benefits	Quantitative (€/kg)

Table 7. *Criteria and attributes for the recyclability assessment.*

In this way, for each criterion, there are as many scores as experts consulted for qualitative attributes and one score for each quantitative attribute. With this data, matrices are formed for each criterion, containing as many columns as consulted experts and as many rows as attributes within the criterion for that strategy. As quantitative criteria yield only one score, the score is replicated as many times as experts consulted.

The process described next is based on the one proposed by ROY ET AL. (2019). Matrices with attribute scores will be referred to as Rij, where $i = 1$ if evaluating the remanufacturing strategy and $i = 2$ if evaluating the recycling strategy. The j designates the criterion being evaluated. The matrix shown below was obtained during the DMF validation. This matrix corresponds to the assessment of the technical suitability of recycling the door assembly.

$$R_{21} = \begin{bmatrix} 7 & 10 & 9 & 7 \\ 6 & 6 & 2 & 5 \end{bmatrix}$$

Next, the matrices R_{ij} for each criterion are multiplied by the so-called W_{ij} matrices, which contain the weights assigned to each attribute because of the application of AHP.

The result of this matrix multiplication yields matrices called I_{ij}, which contain the weighted average score for a criterion by expert, while also considering the objective criteria.

$$I_{21} = W_{21} \times R_{21} \quad (3)$$

$$I_{21} = \begin{bmatrix} 6.67 & 8.67 & 6.69 & 6.34 \end{bmatrix}$$

The three resulting I_{ij} matrices with one row are combined to form one matrix with three rows and as many columns as experts as consulted, called R_i. This matrix is then multiplied by a vector W_i containing the weights assigned to each criterion for the strategy being evaluated. The result of this multiplication is the I_i matrix, which contains as many remanufacturability or recyclability indices as experts consulted.

$$I_2 = W_2 \times R_2 \quad (4)$$

The following operation is taken from the example mentioned above.

$$I_2 = \begin{bmatrix} 0.2 & 0.4 & 0.4 \end{bmatrix} \times \begin{bmatrix} 6.67 & 8.67 & 6.69 & 6.34 \\ 1.24 & 3.18 & 2.46 & 1.86 \\ 8 & 8 & 8 & 8 \end{bmatrix} = \begin{bmatrix} 5.03 & 6.21 & 5.52 & 5.21 \end{bmatrix}$$

The arithmetic means of the values obtained in each I_i matrix is the remanufacturability or recyclability index for that component. In the case of this example, recyclability index equals 5.50.

6.3 Attributes Assessment: Key Performance Indicators

The numerical indicators and the questions that experts answer for the development of the DMF are referred to as attributes and measured by KPIs of the same name.

The goal of the DMF is the analysis of a component, not an organization. Therefore, the KPIs analysed aim to characterize the remanufacturability or recyclability of a component.

Below, KPIs used to evaluate the remanufacturability or recyclability of a component are presented. For each KPI, a description will be provided, its origin will be defined, and the method of calculation and its objective will be presented.

6.3.1 Key Performance Indicators for Remanufacturability

6.3.1.1 Technical Suitability

This KPI is used to assess the suitability of remanufacturing a component based on the ease or even technical feasibility of that remanufacturing. This criterion aims to evaluate the technical feasibility at a higher level, focusing on the state of the art.

Table 8 shows this KPI's breakdown.

Ease of Remanufacturing	
Description	This KPI assesses the current technical qualitatively complexity of remanufacturing a component.
Origin	Evaluation of a sum of remanufacturing attributes extracted from YANG ET AL. (2016): ease of impurity removal and cleaning, resistance to cleaning, ease of receiving conditioning, ease of receiving machining, and ease of receiving additive process.
Method of calculation	Subjective opinion of remanufacturing experts based on ease of impurity removal and cleaning, resistance to cleaning, ease of receiving conditioning, ease of receiving machining, and ease of receiving additive process
Target	The easier the component is to remanufacture, the higher the score.

Table 8. *Ease of Remanufacturing KPI breakdown.*

6.3.1.2 Environmental Performance

These KPIs assess the environmental impacts of remanufacturing components. These impacts are mainly attributed to emissions, the characteristics of the materials used in remanufacturing, and the energy consumed during the process. If the impact is negative for the environment, the score will be lower, whereas if it is neutral or even positive, the score will be higher.

Tables 9, 10. 11, 12 and 13 show this KPIs' breakdown.

Green House Gas Emission	
Description	This KPI calculates the equivalent CO2 emissions of the different greenhouse gases that would be directly emitted during remanufacturing per kilogram of the component.
Origin	Adaptation of Total Green House Gas Emissions described by Graham et al., (2015b) (Total GHG emissions). Includes only direct emission of gases included in the Kyoto Protocol.
Method of calculation	$Green\ House\ Gas\ Emission\ = \frac{\sum CO_2 Equivalent\ (kg\ CO_2)}{Component\ Weight\ (kg)}$ (5)
Target	The lower the value, the higher the score.

Table 9. *Green House Gas Emission KPI breakdown.*

Direct Energy Consumption	
Description	This KPI calculates the direct energy in kilojoules required to remanufacture the component.
Origin	Extracted from (Graham et al., 2015).

Direct Energy Consumption	
Method of calculation	$Direct\ Energy\ Consumption = \sum_{i=0}^{n} Energy\ Consumed\ in\ a\ Process\ (kJ)$ (6) Being “i” a process necessary for the remanufacturing of the component and "n" the total number of processes required for the remanufacturing of the component.
Target	The lower the value, the higher the score.

Table 10. *Direct Energy Consumed KPI breakdown.*

Toxicity during Remanufacturing	
Description	This KPI assesses how toxicity affects the remanufacturability of a component. Some components may not be suitable for remanufacturing because their treatment could pose a risk to the health of workers or environment.
Origin	Adapted from Pillain et al., (2017) (Eco-Toxicity and Human Toxicity). Sum of both KPIs applied to remanufacturing.
Method of calculation	Subjective opinion of remanufacturing experts based on how harmful the treatment would be for health.
Target	The lower toxicity, the higher the score.

Table 11. *Toxicity during Remanufacturing KPI breakdown.*

Material Scarcity	
Description	This KPI assesses how the scarcity of the component’s material. It is possible that the scarcity of a material makes a component containing it more suitable for remanufacturing due to the recovery of high-value materials.
Origin	Adapted from Pillain et al., (2017) (Resource Extraction Concerns). The KPI focuses on the scarcity or difficulty of obtaining materials and does not consider other factors such as their difficulty to be extracted.
Method of calculation	Subjective opinion of remanufacturing experts based on the scarcity of raw materials for the manufacturing or remanufacturing of the component.
Target	The scarcer the material, the higher the score.

Table 12. *Material Scarcity KPI breakdown.*

Recycled Material Used	
Description	This KPI calculates the percentage of recycled material that can be used in the remanufacturing of the component.
Origin	Extracted from Graham et al., (2015b).
Method of calculation	$Recycled\ Material\ Used = \frac{Recycled\ Added\ Wieght\ (kg)}{Added\ Weight\ During\ Reman\ (kg)} \times 100$ (7)

Recycled Material Used	
Target	The higher the value, the higher the score.

Table 13. *Recycled Material Used KPI breakdown.*

6.3.1.3 Economic performance

The economic performance has been assessed with a single score. It is understood that different types of costs or benefit does not have different importance, but it is in the overall comparison with a newly manufactured piece that the appropriateness of remanufacturing for the component is determined.

An approximate calculation of the potential remanufacturing cost of the component could be carried out using (Anthony & Cheung, 2017):

$$C_{RM} = \left((T_d + T_a) \times L \times f\right) + \left(P_f \times C_f\right) + ((P_{pd} + \left(P_f \times P_e\right) - \left(P_{pd} \times P_f \times P_e\right)) \times C_p) \quad (8)$$

Where:

C_{rm} remanufacturing cost (€)

T_d disassembly time (min)

T_a assembly time (min)

L Labour rate (€/min)

f disassembly depth factor

P_f probability of fastener failure in disassembly and assembly

C_f cost of fastener failure (€)

P_{pd} probability of part failure in disassembly and assembly

P_{pe} probability of part failure in fastening method extraction

C_P cost of part failure (€)

Where disassembly deep factor can be calculated by using:

$$f = \frac{Number\ of\ assemblies\ to\ disassemble}{Total\ number\ of\ assemblies} \quad (9)$$

In this case, the detachable pieces that make up the component are referred to as "assemblies."

An in-depth explanation of this equation can be found in Shu & Flowers 1999).

This is based on the following assumptions and details (ANTHONY & CHEUNG, 2017):

- It takes the same time to disassemble each assemble.
- Disassembly divides an assembly into fundamental pieces and low-level assemblies.
- The time for individual pieces separation equals the disassembly time for the whole assembly,
- Model treats as a component when entire assembly is targeted.

However, this is not a realistic assumption. For example, when considering a component fixed with 50 screws against one fixed with quick joints, and then quick joints will be easier and faster to disassemble (ANTHONY & CHEUNG, 2017).

This method focuses on the disassembly and assembly times during remanufacturing. It considers the cost of labour and the probability of unsuccessful remanufacturing attempts. The calculation of the probability of component remanufacturing is beyond the scope of this document. However, it does not include the costs associated with repairing or returning components to their original state.

For the example carried out in this thesis, a simpler formula has been developed, considering the price of costs associated with repairs, while excluding the probability of remanufacturing failure. Although, this probability and other expenses (such as transportation or storage) will be considered as “miscellaneous costs.”

$$Remanufacturing\ Cost = T_d \times L_d + T_r \times L_r + C_{raw} + Miscellaneous\ Costs \quad (10)$$

Where:

T_d disassembly time (min)

L_d labor rate of disassemblers (€/min)

T_r pieces' restorage and reassembly time (min)

L_r labor rate of restorers (€/min)

C_{raw} raw materials' cost (€)

Table 14 shows a breakdown of the KPI described.

Component Value Ratio	
Description	This KPI calculates the difference between the cost of remanufacturing the component and the cost of manufacturing it from scratch. It considers all the expenses associated with remanufacturing.
Origin	Adapted from (GRAHAM ET AL., 2015b) (Product Margin). The new KPI focuses the comparison on the economic difference in production and not on the profit margin from its sale.
Method of calculation	$Component\ Value\ Ratio = \frac{Cost\ of\ Remanufacturing\ (€)}{Cost\ of\ Manufacturing\ (€)} \times 100$ (11)
Target	The lower the value, the higher the score.

Table 14. *Component Value Ratio KPI breakdown.*

6.3.2 Key Performance Indicators for Recycling

6.3.2.1 Technical Suitability

These KPIs are used to assess the suitability of recycling a component based on the ease or even technical feasibility of that recycling. The first KPI evaluates the technical feasibility at a higher level, focusing on the state of the art.

The second KPI focuses on the quality of the potential recycling process. It is essential to understand that recycling a component does not necessarily mean that its materials will regain the properties suitable to component's production.

Tables 15 and 16 show this KPIs' breakdown.

Ease of Recyclability	
Description	This KPI qualitatively assesses the technical complexity of the recycling of a component at the time of analysis.
Origin	Adaptation of the "Ease of Remanufacturability" KPI.
Method of calculation	Subjective opinion of recycling experts based on the ease with which the component can be transformed into usable raw materials through appropriate treatment.
Target	The easier the component is to recycle, the higher the score.

Table 15. *Ease of Recycling KPI breakdown.*

Quality of Recycling (QoR)	
Description	This KPI assesses the quality of potential component recycling. The higher the downcycling, the lower the likelihood of reintegrating it into a new vehicle.
Origin	Self-developed.

Quality of Recycling (QoR)	
Method of calculation	Subjective opinion of recycling experts based on the quality of materials obtained after recycling the component.
Target	The better the quality of the possible recycle, the higher the score.

Table 16. *Quality of Recycling KPI breakdown.*

6.3.2.2Environmental performance

The evaluation of the environmental performance of recycling is carried out in the same manner as for remanufacturing, except for the KPI called "Recycled Material Used," which does not apply in this case. The rest of the KPIs are assessed in the same way as for remanufacturing, having the same origin and target.

6.3.2.3 Economic performance

The economic performance of recycling is evaluated through the profit obtained from selling materials for recycling.

Table 17 shows this KPI breakdown.

Profit from Recycling	
Description	This KPI calculates the benefits that would be obtained from selling the component for recycling.

Profit from Recycling	
Origin	Adapted from Anthony & Cheung, (2017).
Method of calculation	$Profit\ from\ Recycling = Component\ Weight\ (kg) \times Recycled\ Material\ Price\ (€/kg)$ *(12)*
Target	The higher the value, the higher the score.

Table 17. *Profit from Recycling KPI breakdown.*

7 Verification and Validation of the Assessment System

For the DMF’s validation, a BMW 5 Series’ door is taken as an example. BMW Group provided a spreadsheet containing 1923 subassemblies from the five doors of a BMW. The spreadsheet also includes the weights of each of the subassemblies and their materials.

To reduce the number of decisions to be made, the following steps were followed:

1. The example focuses on the driver's door, so data pertaining to subassemblies belonging to the front right door, rear doors, and trunk are eliminated.
2. Subassemblies are grouped based on the parts they belong to, to assess larger elements and reduce the number of decisions. This results in grouping all subassemblies into 70 parts.
3. As each of the parts must be evaluated against 16 KPIs, the values of the subassemblies' weights are summed to obtain the value of the parts. Among the 70 parts, 58 of them weigh less than 500 g, and half of the 70 parts do not exceed 100 g. It is then decided to evaluate only the 10 heaviest parts, which make up the main body of the door.

Table 18 displays the 10 components that are being assessed and their weights.

Part name	Weight (g)
1. Door Assembly	14515.72
2. Monolithic Safety Glass	2900
3. Edge Protections	2416
4. Light-weight Carrier Including Window Regulator	1655.43
5. Window Guide	933.2
6. Door Module Carrier	874.8
7. Central Locking System	565.11
8. Door Rubber Adhesive Seal	560
9. Channel Cover	504.2

Part name	Weight (g)
10. Rear-view Mirror Housing	459

Table 18. *Analysed parts and weights.*

For the data analysis, main materials of the parts have been classified. The heaviest subcomponents are taken into consideration, which together make up at least 75% of the weight of the part. This simplification is due to the large number of subcomponents listed, with materials that account for less than 1% of the weight of the part.

Table 19 lists the materials that have been considered for the framework, their respective weights, and the percentage of each material within the part.

Component	Material	Material Weight	Material Percentage (%)
Door Assembly	Steel	14515.72	100.00
Monolithic Safety Glass	Green Glass	2900	100.00
Edge Protection	EPDM	1823.09	78.58
	Aluminium	496.96	21.42
Light-Weight Carrier Including Window Regulator	PP	520.14	41.28
	Aluminium	252	20.00
	Glass Fibre	194.71	15.45
	Steel	164.62	13.07
	PA	70.48	5.59
	Ferrite Magnet	57.96	4.60
Window Guide	EPDM	805.52	100
Door Module Carrier	EPDM	414.22	100
Central Locking System	Steel	233.54	53.99
	PBT	117.86	27.25

Component	Material	Material Weight	Material Percentage (%)
	POM	70	16.18
	Iron Oxide	11.18	2.58
Rear-View Mirror Housing	Aluminium	307	72.32
	PC	117.5	27.68
Rubber Adhesive Seal	Aluminium	538.86	100
Channel Cover	EPDM	303	70.63
	Aluminium	126	29.37

Table 19. *Materials, weight, and percentage of weight per material within the part.*

7.1 Qualitative KPIs Score

Four experts conducted the scoring of quantitative KPIs through an online survey. Out of the four experts, three are academics with a focus on remanufacturing and vehicle recycling. The fourth expert is an industry professional, specifically in end-of-life vehicles.

Table 20 and 21 display experts' average score for each part and qualitative attribute.

Part	Ease of Remanufacturing	Toxicity during Remanufacturing	Remanufacturing Material Scarcity
Door Assembly	6.75	4.50	3.25
Monolithic Safety Glass	4.50	4	3.25
Edge Protections	2	4.75	3.25
Light-weight Carrier	6.25	5.50	4.50
Window Guide	3.25	4.50	4
Door Module Carrier	5.50	5.25	4.75

Part	Ease of Remanufacturing	Toxicity during Remanufacturing	Remanufacturing Material Scarcity
Central Locking System	5	4.25	5.50
Rubber Adhesive Seal	2.25	4	2.75
Channel Cover	3.50	5	4.50
Rear-view Mirror Housing	6	5.75	5

Table 20. *Average expert score on qualitative remanufacturing KPIs.*

Part	Ease of Recycling	Quality of Recycling	Toxicity during Recycling	Recycling Material Scarcity
Door Assembly	8.25	4.75	4.75	3.75
Monolithic Safety Glass	7.25	5.75	4.25	3.25
Edge Protections	5.25	4.50	5.50	4
Light-weight Carrier	5.50	5	5.50	4.75
Window Guide	5.25	4	5.25	4.25
Door Module Carrier	4.75	4.50	5	4
Central Locking System	4.25	4	4	5.5
Rubber Adhesive Seal	4.25	3.25	5	3.75
Channel Cover	5	3.50	4.25	4.50

Part	Ease of Recycling	Quality of Recycling	Toxicity during Recycling	Recycling Material Scarcity
Rear-view Mirror Housing	4.75	3.75	4.75	4.25

Table 21. *Average expert score on qualitative recycling KPIs.*

7.2 Quantitative KPIs Score

The quantitative KPIs score has been conducted using tools for product lifecycle analysis and data extracted from the literature.

Data related to remanufacturing is evaluated using literature data on manufacturing since there is very little data available on emissions or energy consumption in the remanufacturing processes of specific vehicle parts. As defined in this document, the remanufacturing process brings the product to a state like manufacturing (LOW ET AL., 1997). Therefore, for the strategies comparison and their evaluation for specific parts, data extracted from the manufacturing process can be used, even though this data is approximate and depend on many conditions that cannot be reliably assessed without carrying out the actual process with each of the parts.

Materials have been grouped into six categories: steel, plastic, glass, rubber aluminium and mixed metals.

In the case of Direct Energy Consumption and Green House Gas Emissions, data related to the materials comprising each part has been extracted by weight. Subsequently, the weight of each material in the part has been multiplied by the weight-specific value defined in the literature.

Table 22 and 23 show emissions and energy consumption per kg of material during manufacturing.

Material	Green House Gas Emissions (kg CO_2eq./kg)
Steel	5.51
Plastic	8.07
Glass	1.47

Material	Green House Gas Emissions (kg CO_2eq./kg)
Rubber	13.58
Aluminium	5.51
Mixed metals	7.38

Table 22. *Kilograms of CO_2 emissions per kg of material during manufacturing (SATO ET AL., 2018).*

Material	Direct Energy Consumption (kJ/kg)
Steel	63.97
Plastic	108.65
Glass	55.13
Rubber	153.75
Aluminium	341.92
Mixed metals	72.27

Table 23. *Energy consumed during manufacturing per material (SATO ET AL., 2018).*

The sum of all multiplications constitutes the value to be assessed for that part. After defining the intervals that correlate data with scores, it is observed which interval the previously obtained value falls into, and the corresponding score is assigned.

For example, the channel cover is composed of EPDM (rubber) and aluminium. The 0.303 kg of rubber in the part are multiplied by 13.58 kg of CO_2eq. emitted per kg of remanufactured rubber and added to the 0.126 kg of aluminium in the part multiplied by the 5.51 kg of CO_2eq. emitted per kg of remanufactured aluminium. The result is 4.81 kg of CO_2eq. emitted because of the remanufacturing of the part. This value falls between 4.5 and 5.5 kg of equivalent CO_2eq. and therefore receives a score of 6 for the DMF.

Table 24 displays emissions during remanufacturing intervals for each score and table 15 energy consumption during remanufacturing intervals for each score.

Tables 26 and 27 show emissions and energy consumption during remanufacturing respectively and score for each part.

Green House Gas Emissions (kg CO_2eq.)	**Score**
≤ 1.5	10
1.5 – 2.5	9
2.5 – 3.5	8
3.5 – 4	7
4.5 – 5	6
5.5 – 6.5	5
6.5 – 7.5	4
7.5 – 8.5	3
8.5 – 9.5	2
≥ 10	1

Table 24. *Emission during remanufacturing intervals for each score.*

Direct Energy Consumption (kJ)	**Score**
0 – 50	10
50 - 150	9
150 – 250	8
250 – 350	7
350 – 450	6
450 – 550	5
550 – 650	4
650 – 750	3
750 – 850	2
> 850	1

Table 25. *Energy consumption during remanufacturing intervals for each score.*

Part	Green House Gas Emissions (kg CO_2eq.)	Score
Door Assembly	79.98	1
Monolithic Safety Glass	4.26	7
Edge Protection	27.50	1
Light-Weight Carrier Including Window Regulator	8.14	3
Window Guide	4.44	7
Door Module Carrier	5.63	5
Central Locking System	2.89	8
Rear-View Mirror Housing	2.64	8
Rubber Adhesive Seal	2.97	8
Channel Cover	4.81	6

Table 26. *Emissions during remanufacturing and score for each part.*

Part	Direct Energy consumption (kJ)	Score
Door Assembly	928.57	1
Monolithic Safety Glass	159.88	8
Edge Protection	450.22	5
Light-Weight Carrier Including Window Regulator	175.79	8
Window Guide	123.85	9
Door Module Carrier	63.69	9
Central Locking System	36.16	10
Rear-View Mirror Housing	117.74	9
Rubber Adhesive Seal	184.25	9
Channel Cover	89.67	9

Table 27. *Energy consumption during remanufacturing and score for each part.*

The evaluation of the Geen House Gas Emissions and Direct Energy Consumption for the recycling strategy has been conducted in the same manner, using data extracted from the Waste Reduction Model (WARM) tool created by the United States Environmental Protection Agency (EPA) (Waste Reduction Model (WARM), 2022). This tool assesses the material-specific impacts of common EOL strategies for products.

Table 28 and 29 show emissions and energy consumption per kg of material during recycling.

Material	Green House Gas Emissions (kg CO_2eq./kg)
Steel	1.93
Plastic	0.93
Glass	0.28
Rubber	0.38
Aluminium	7.20
Mixed Metals	4.39

Table 28. *Kilograms of CO_2eq. emissions per kg of material during recycling (WASTE REDUCTION MODEL (WARM) | US EPA, 2022).*

Material	Direct Energy consumption (KJ/kg)
Steel	10.73
Plastic	36.95
Glass	2.25
Rubber	3.80
Aluminium	120.11
Mixed Metals	70.21

Table 29. *Energy consumed during recycling per material (WASTE REDUCTION MODEL (WARM) | US EPA, 2022).*

In the same way, intervals have been defined and notes assigned for each of the parts and the KPIs.

Table 30 displays emissions during recycling intervals for each score and table 31 energy consumption during recycling intervals for each score.

Tables 32 and 33 show emissions and energy consumption during recycling respectively and score for each part.

Green House Gas Emissions (kg CO_2eq./kg)	**Score**
< 1.5	10
1.5 – 2.5	9
2.5 – 3.5	8
3.5 – 4.5	7
4.5 – 5.5	6
5.5 – 6.5	5
6.5 – 7.5	4
7.5 – 8.5	3
8.5 – 9.5	2
> 9.5	1

Table 30. *Emission during recycling intervals for each score.*

Direct Energy Consumption (MJ)	**Score**
< 15	10
15 – 25	9
25 – 35	8
35 – 45	7
45 – 55	6
55 – 65	5
65 – 75	4
75 – 85	3
85 – 95	2

Direct Energy Consumption (MJ)	Score
> 95	1

Table 31. *Energy consumption during recycling intervals for each score.*

Part	Green House Gas Emissions (kg CO_2eq.)	Score
Door Assembly	28.02	1
Monolithic Safety Glass	0.81	10
Edge Protection	4.27	7
Light-Weight Carrier Including Window Regulator	2.99	8
Window Guide	0.31	10
Door Module Carrier	0.16	10
Central Locking System	0.67	10
Rear-View Mirror Housing	2.32	9
Rubber Adhesive Seal	3.88	7
Channel Cover	1.02	10

Table 32. *Emissions during recycling and score for each part.*

Part	Direct Energy Consumption (MJ)	Score
Door Assembly	155.74	1
Monolithic Safety Glass	6.52	10
Edge Protection	66.61	4
Light-Weight Carrier Including Window Regulator	58.36	5
Window Guide	3.06	10
Door Module Carrier	1.57	10
Central Locking System	10.23	10
Rear-View Mirror Housing	41.22	7

Part	Direct Energy Consumption (MJ)	Score
Rubber Adhesive Seal	64.72	5
Channel Cover	16.28	9

Table 33. *Energy consumption during recycling and score for each part.*

The amount of recycled material used in the production of each part varies depending on the material used for its manufacturing. The data was extracted from two brands' sustainability reports, PSA GROUP (2020) and BMW GROUP (2022). This way, the Recycled Material Used for each part is calculated by multiplying the percentage of recycled material for each material by the percentage of that material in the part. Currently, the use of recycled glass in the industry is not considered, and the appearance of mixed metals as recycled material has been disregarded.

Table 34 shows the average percentage of secondary raw material in vehicle's manufacturing.

Material	Average Secondary Raw Material (%)
Steel	30
Plastic	10
Glass	0
Rubber	10
Aluminium	30
Mixed Metals	0

Table 34. *Percentage of secondary raw material in vehicles' manufacturing per material from (PSA GROUP, 2020) (BMW GROUP, 2022).*

Considering the amount of secondary raw material used in vehicles, intervals of the relationship between the percentage of recycled raw material and their respective scores are defined in Table 35. With these intervals defined, parts are scored based on the percentage of recycled raw material used in their production in Table 36.

Recycled Material Used (%)	Score
> 30	10
30 - 24	9
24 - 21	8
21-18	7
18 - 15	6
15 -12	5
12 - 9	4
9 - 6	3
6 - 3	2
> 3	1

Table 35. *Recycled material used during remanufacturing intervals for each score.*

Part	Recycled Material Used (%)	Score
Door Assembly	30.00	10
Monolithic Safety Glass	0.00	1
Edge Protection	8.16	3
Light-Weight Carrier Including Window Regulator	14.61	5
Window Guide	10.00	4
Door Module Carrier	10.00	4
Central Locking System	20.54	7
Rear-View Mirror Housing	24.46	9
Rubber Adhesive Seal	30.00	10
Channel Cover	7.36	3

Table 36. *Recycled material used during manufacturing and score for each part.*

For the Component Value Ratio, certain approximations have been made due to the uncertainty in the price and time of the remanufacturing process for each part. First, the selling price of the parts is considered, not their manufacturing cost, which is unknown. The prices have been obtained from a specialized website for the sale of original BMW parts (www.getBMWparts.com).

Next, the remanufacturing cost is calculated as the sum of three values: the labour cost responsible for disassembling and reconditioning the part, the cost of raw materials, and variable costs. The cost of disassembly and reconditioning considers the number of subassemblies for each part, multiplies it by the average wage per minute (0.35€/min, 21€/h) of an automotive industry worker in Germany (ECONOMIC RESEARCH INSTITUTE, 2023) and by an approximate ten-minute duration that considers both disassembly and reconditioning for each subassembly.

For the raw material cost, the weight of the raw material is multiplied by the current approximate price for each part. Variable costs amount to 10% of the sum of the two previous values (LOW ET AL., 1997). Finally, the relationship between the remanufacturing cost and the retail selling price is calculated, obtaining the percentage that the strategy represents in the market value for each part.

A full cost breakdown and the Component Value Ratio calculation for each part is shown in Table 37.

Part	Selling Price (€)	Subassemblies Number	Labour Price (€)	Raw Materials (€)	Miscellaneous Cost (€)	Component Value Ratio (%)
Door Assembly	110.02	29	101.5	10.89	11.24	112.37
Monolithic Safety Glass	213.41	3	10.5	3.63	1.41	7.28
Edge Protection	359.36	4	14	2.99	1.70	5.20
Light-Weight Carrier Including Window Regulator	272.45	106	371	2.11	37.31	150.64
Window Guide	114.48	12	42	1.61	4.36	41.90
Door Module Carrier	40.48	11	38.5	0.83	3.93	106.87

Part	Selling Price (€)	Subassemblies Number	Labour Price (€)	Raw Materials (€)	Miscellaneous Cost (€)	Component Value Ratio (%)
Central Locking System	243.95	98	343	0.56	34.36	154.92
Rear-View Mirror Housing	109.24	5	17.5	0.85	1.83	18.48
Rubber Adhesive Seal	131.17	3	10.5	1.08	1.16	9.71
Channel Cover	58.81	9	31.5	0.86	3.24	60.52

Table 37. *Cost breakdown and Component Value Ratio for each part.*

In Tables 38 and 39, the intervals are defined for each percentage, taking into account that a percentage greater than 100% indicates that the operation is not economically viable. The score is then calculated for each part.

Score	Component Value Ratio (%)
10	< 15
9	15 - 25
8	25 - 35
7	35 - 45
6	45 - 55
5	55 - 65
4	65 - 75
3	75 - 85
2	85 - 95
1	> 95

Table 38. *Component Value Ratio intervals for each score.*

Part	Component Value Ratio (%)	Score
Door Assembly	112.37	1
Monolithic Safety Glass	7.28	10
Edge Protection	5.20	10
Light-Weight Carrier Including Window Regulator	150.64	1
Window Guide	41.90	7
Door Module Carrier	106.87	1
Central Locking System	154.92	1
Rear-View Mirror Housing	18.48	9
Rubber Adhesive Seal	9.71	10
Channel Cover	60.52	4

Table 39. *Component Value Ratio and score for each part.*

The benefits derived from recycling various materials have also been obtained from the WARM tool, which considers all forms of income generated from material management (Waste Reduction Model (WARM), 2022), as shown in Table 40.

Material	Benefit ($/kg)
Steel	0.25
Plastic	1.37
Glass	0.49
Rubber	1.37
Aluminium	3.77
Mixed Metals	1.49

Table 40. *Benefit from recycling per kg of material* (Waste Reduction Model (WARM), 2022)

Table 41 display the intervals that have been defined and scores assigned for each of the parts depending on benefits from recycling.

Benefit ($)	Score
> 4.5	10
4 - 4 .5	9
4	8
3 - 3.5	7
2.5 – 3.5	6
2 - 2.5	5
1.5 - 2	4
1 - 1.5	3
0.5 - 1	2
0 - 0.5	1

Table 41. *Benefit from recycling intervals for each score.*

Part	Benefit ($)	Score
Door Assembly	3.57	8
Monolithic Safety Glass	1.42	3
Edge Protection	4.38	9
Light-Weight Carrier Including Window Regulator	1.98	4
Window Guide	1.11	3
Door Module Carrier	0.57	2
Central Locking System	0.33	1
Rear-View Mirror Housing	1.32	3
Rubber Adhesive Seal	2.03	5
Channel Cover	0.89	2

Table 42. *Benefit from recycling and score for each part.*

8 Results

Tables 43 and 44 display the results of applying the AHP to the pairwise comparisons made by the experts.

In the remanufacturing case, results indicate that experts consider economic performance to be more important, followed by technical suitability, and environmental performance.

Direct Energy Consumption has been considered the KPI with the highest weight, while Toxicity during Remanufacturing has been assigned the lowest weight within environmental performance.

Criteria	Criteria Weighting	Attribute	Partial Attribute Weight	Global Attribute Weight
Technical Suitability	0.35	Ease of Remanufacturing	1	0.35
Environmental Performance	0.15	Green House Gas Emission	0.23	0.03
		Direct Energy Consumption	0.29	0.04
		Toxicity during Remanufacturing	0.12	0.02
		Remanufacturing Material Scarcity	0.20	0.03
		Recycled Material Used	0.17	0.03
Economic Performance	0.5	Component Value Ratio	1	0.50

Table 43. *Remanufacturing AHP outcome.*

In the case of recycling, economic and environmental performance received the same weight, followed by technical suitability.

Ease of Recycling was given greater weight than Quality of Recycling. Green House Gas Emission and Direct Energy Consumption are the KPIs with the highest weight within environmental performance, while Toxicity during Recycling received the lowest weight.

Criteria	**Criteria Weighting**	**Attribute**	**Partial Attribute Weight**	**Global Attribute Weight**
Technical Suitability	0.20	Ease of Recycling	0.67	0.13
		Quality of Recycling	0.33	0.07
Environmental Performance	0.40	Green House Gas Emission	0.31	0.12
		Direct Energy Consumption	0.31	0.12
		Toxicity during Remanufacturing	0.14	0.06
		Remanufacturing Material Scarcity	0.24	0.10
Economic Performance	0.40	Benefits	1	0.40

Table 44. *Recycling AHP outcome.*

Table 45 compiles the results of applying Fuzzy MCDM method to the objectively and subjectively obtained scores from data and experts' opinion.

Four of the vehicle door parts received a rating of less than four in the assessment of their remanufacturability, indicating that they are not suitable for this strategy. All parts were assessed as recyclable. The rear-view mirror housing turned out to be the most suitable part for remanufacturing and edge protections for recycling.

Part	**Remanufacturing Score**	**Recycling Score**	**Decision**
Door Assembly	3.36	5.50	*Recycling*
Monolithic Safety Glass	7.34	5.57	*Remanufacturing*
Edge Protections	6.20	6.66	*Recycling*
Light-weight Carrier	3.48	5.05	*Recycling*
Window Guide	5.55	5.35	*Remanufacturing*
Door Module Carrier	3.30	4.88	*Recycling*
Central Locking System	3.35	4.46	*Recycling*
Rubber Adhesive Seal	6.84	4.92	*Remanufacturing*
Channel Cover	4.10	4.71	*Recycling*
Rear-view Mirror Housing	7.72	4.74	*Remanufacturing*

Table 45. *Global scores and decided strategy for each part.*

Table 46 shows emissions, energy consumed and benefit of following the DMF chosen strategies. The economic benefit of remanufacturing has been calculated as the price of the part on the second-hand market minus the costs of carrying out the remanufacturing operation.

Part	**Decision**	**Emissions** $(\mathbf{kg\ CO_2eq.})$	**Energy Consumption (MJ)**	**Benefit (€)**
Door Assembly	*Recycling*	28.02	155.74	3.57

Part	Decision	Emissions $(\mathbf{kg\ CO_2 eq.})$	Energy Consumption (MJ)	Benefit (€)
Monolithic Safety Glass	*Remanufacturing*	4.26	0.93	197.87
Edge Protection	*Recycling*	4.27	66.61	4.38
Light-Weight Carrier Including Window Regulator	*Recycling*	2.99	58.36	1.98
Window Guide	*Remanufacturing*	4.44	0.12	66.51
Door Module Carrier	*Recycling*	0.16	1.57	0.57
Central Locking System	*Recycling*	0.67	10.23	0.33
Rear-View Mirror Housing	*Remanufacturing*	2.64	0.12	89.06
Rubber Adhesive Seal	*Recycling*	3.88	64.72	2.03
Channel Cover	*Remanufacturing*	4.81	0.09	23.21
Sum		**56.14**	**358.49**	**389.51**

Table 46. *Emissions, energy consumed and economic benefit resulting from the DMF implementation.*

9 Conclusion and Outlook

This Master's Thesis has developed a DMF designed to assist vehicle disassemblers in determining whether a component should be disassembled into its constituent parts. In the case of the validation conducted, the conclusion is reached that it is advisable to disassemble the door into its parts, as all of them are suitable for recycling, and six of them are additionally suitable for remanufacturing. The DMF concludes that four of these parts should preferably be remanufactured, while the remaining six should be recycled.

Following an examination of the current state of decision-making for end-of-life vehicles, it can be concluded that the immediate application of a DMF like the one presented is very challenging. As developed in this document, currently only a few specific components are targeted for disassembly. These components are not individually evaluated, but rather, it is generally the same ones being considered. The reason for their disassembly is usually due to legal requirements. Therefore, it is not trivial to imagine how a screening process using the presented DMF could be systematically carried out.

One option would be to adapt the DMF into software, where operators only need to visually evaluate the components and input specific data to assess the various qualitative attributes of the component. The program could quickly use this data to evaluate the possibilities for the component's second life and inform the operator whether the component should be disassembled or not, along with the strategy to follow for its treatment. For this evaluation, the program could store the assigned weights for criteria and attributes scored by experts. Another advantage is that these weights can be updated at any time for each component. Thus, experts from all over the world would be collaborating in the decision-making process for an individual operator. The work of the operators could also be facilitated by dividing some attributes into smaller evaluations, which may differ based on the component being evaluated. Thus, it would be possible to include attributes dependent on the condition of the part, which the operator could assess using tools or a simple visual inspection.

A significant challenge found throughout the research was the lack of transparency in the data provided by OEMs. This has been the main barrier in the development of the thesis – the lack of data on remanufacturing and recycling (such as costs, emissions, or energy consumption) that OEMs do not provide, and in some cases, are likely unaware of. For the DMF validation, data had to be relied upon from existing literature. Often, these data did not align perfectly with what would be expected in a real-world scenario due to differences in the brand providing the data or variations in research locations, among other factors.

Regrettably, BMW did not grant permission to review the catalogue used by their employees for decision-making during vehicle disassembly. Additionally, detailed numerical data regarding costs, emissions, energy consumption, or recycled materials were not provided, limiting the ability to conduct a comprehensive evaluation.

In conclusion, individually evaluating the components of an ELV would yield economic and environmental benefits. This transformation relies significantly on the commitment and transparency of OEMs. Consequently, the realm of decision-making in ELVs holds considerable potential for future development.

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VI Sworn Declaration

Ich erkläre hiermit eidesstattlich, dass ich die vorliegende Arbeit selbständig angefertigt habe. Die aus fremden Quellen direkt oder indirekt übernommenen Gedanken sind als solche kenntlich gemacht.

Die Arbeit wurde bisher keiner anderen Prüfungsbehörde vorgelegt.

[English translation:

I hereby declare on oath that I have independently produced the present work. The thoughts taken directly or indirectly from external sources are marked as such.

The work has not been submitted to any other examination board.]*

Garching, den 16.11.2023

Miguel Carballar

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* *Please note that in case of doubt the German translation is legally binding.*