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Sustainability in Automotive: Closing the Loop with End-of-Life Vehicle Disassembly

A Master's Thesis submitted for the degree of
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supervised by
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Vienna, 15.08.2025

Affidavit

I, **FLORIAN HANSCHMANN**, hereby declare

1. that I am the sole author of the present Master's Thesis, "SUSTAINABILITY IN AUTOMOTIVE: CLOSING THE LOOP WITH END-OF-LIFE VEHICLE DISASSEMBLY", 80 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

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Abstract

In end-of-life vehicles (ELV) recycling currently about 90% of the material can be recovered and reused in different industries. Most of the recycled content lacks material purity to maintain required properties of the material to be reused in a vehicle itself. The state-of-the-art shredding and sorting approach implies material contamination decreasing the quality outcome. By increasing the material purity prior to the recycling processes a higher quality without additional effort during recycling could be achieved. The thesis analyses the potential of ELV disassembling to reveal valuable materials for recycling compared to the shredding and sorting approach.

In qualitative interviews with industry experts along the vehicle lifecycle the technological, ecological and economic aspects of a potential disassembling approach are discussed and analyzed. In addition, industry investigation identifies the key impact factors creating the baseline for a multi-future scenario study. A business evaluation including a sensitivity investigation completes the framework for the disassembly approach.

As a result, the thesis suggests a disassembling concept separating the ELV into modules followed by clean separation processes if required for a specific module according to recyclability. The depth drives investment in addition to vision and recognition systems that can handle the variety of vehicle brands, models and model years. Manual processes show high sensitivity to the process depth and operational costs while the more beneficial automated disassembly line is mainly impacted by the material market prices which create the revenue for the process. Another economic weight is the supply of ELVs which is currently seen interrupted by export trends and requires regulation or motivation systems. To limit additional costs and emissions for logistics, disassembly installations should be regionally decentralized.

The circular economy benefits from collaborations across the industry, and this analysis strengthens the opposition of working in silos, which is predominant in a competitive environment. The competition of a disassembly approach is the improvement of sorting processes after shredding. When those developments enable the required recycling material purity an additional disassembling process would be obsolete. In the same way design for recycling prioritizing mono material components can simplify or supersede disassembly.

The thesis displays those important indicators, suggests concepts for technology and business evaluation and proposes details to be researched for a viable option to improve circular economy in automotive.

1 Introduction

The automotive industry continues to follow a linear economy. Raw material gets extracted and processed, the product is designed and manufactured, then operated and serviced and at the end scrapped. The scrapped metal can be recycled and reused in other industries, most of the new vehicles are designed and built from new extracted materials (Berzi et al., 2013), (Soo et al., 2016).

Linear economy aims for exploitation of materials, processing of the materials into products, consumption of products and waste at the end. While the material extraction reaches limitations based on geological restraints and geopolitical cutbacks that prevent global availability, waste becomes a health and safety problem for humankind. To ensure an ecological and economic sustainable future, the linear economy should be transferred into sustainable models rather sooner than later (VCÖ, 2022).

Some approaches address this problem. Besides the transformation in engine technologies, the automotive industry develops and implements methods to reduce its carbon footprint. There are also early approaches to the circular economy. Some of the initiatives such as increased recycling content, reduced manufacturing energy consumption as well as second life for components and manufacturing devices are driven by automotive companies, material suppliers and research institutes (Bito, 2024), (RenaultGroup, 2025), (Volk, 2025), (Schmidt, 2024).

When a vehicle gets scrapped the material is mixed with different elements from various functional parts. The contamination prevents the recycling into high quality materials which demand cleanliness of incoming composition. Those materials might be reusable in the car itself or other industries at a wider range compared to current recycled metals (Soo et al., 2016). The motivation and goal of this thesis is the path towards precious recycling grades.

There are two main approaches. Currently the end-of-life vehicle is shredded and the shredded material sorted with challenges of material impurity (Berzi et al., 2013). Research in post-shredding sorting processes may improve the outcome in the future. This thesis focusses on an additional process step: the disassembly of the vehicle to sort materials prior to the recycling process. Higher cleanliness of the outcome material composition may increase the value of the material by simplifying the recycling process to get to the desired material grade.

To identify the potential of a disassembly this thesis analyses current approaches in research and industry, studies interviews with experts along the vehicle life cycle and analysis scenarios and economical key drivers. The outcome is the evaluation of the technical and economic potential of the disassembly as well as the estimate about key drivers for a disassembling process in terms of technology, sustainability and economy.

2 Background

2.1 Emission regulations

Since the start of the 21st century global greenhouse emissions continue to increase. In 2023, global GHG emissions reached a record of 53 gigatons (Gt) CO_2 equivalent (CO_{2eq})[1]. Besides ongoing international efforts for emission reduction, emissions continued to grow by 1.9% compared to the year before (Crippa M., 2024). Transportation and mobility have the second biggest impact on global greenhouse emissions as shown in Figure 1. The category transport, summing up to 8.4 Gt CO_{2eq}, includes emissions from road, rail, ship and aviation mobility.

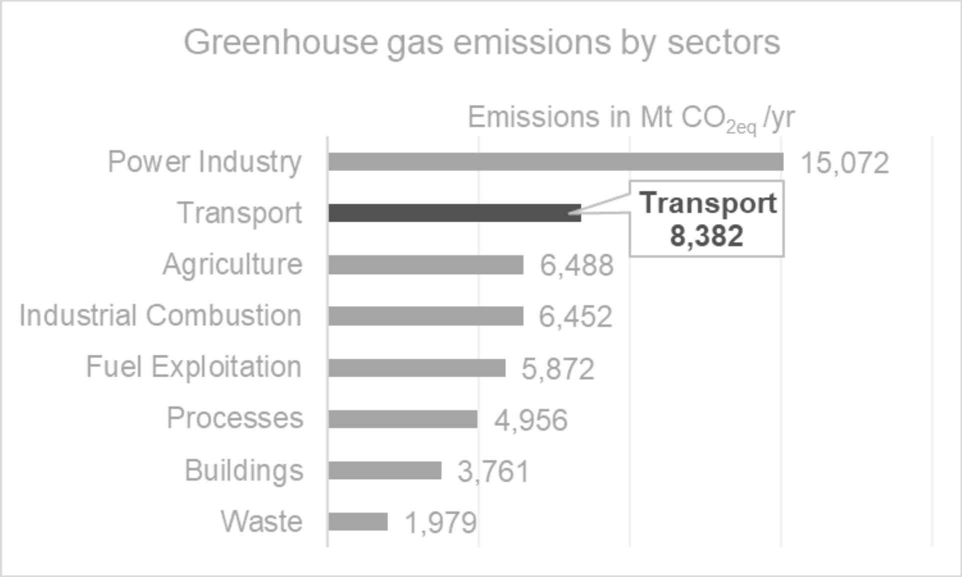

Figure 1 Global greenhouse gas emissions in 2023 by sectors based on EDGAR data (Crippa M., 2024)

Within this sector of transportation, road mobility dominates with a share of about 70% based on an analysis of 2019 with the assumption that the share has not changed drastically between 2019 and 2023 (Jaramillo, 2022).

To reduce emissions, changes in current mobility are required. The Intergovernmental Panel on Climate Change (IPCC) therefore suggests programs to reduce transport demands and increase the efficiency of transportation. Besides changes in the infrastructure and digitalization as well as programs for changing mobility behaviors, shared economy and

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[1] The $CO2_{eq}$ accounts the emissions from various greenhouse gases and provides a more comprehensive measure of climate impact

circular economy can contribute to a decrease in greenhouse gas emissions (Jaramillo, 2022). Chapter 2.2 amplifies the aspects of circular economy.

The emissions of a car can be separated into emissions caused by the manufacturing process and the emissions caused during the usage of the road vehicle. To stimulate the production of cars with reduced emissions, regulations are globally in place. In the European Union since 2025 the targets have been based on the Worldwide harmonized Light vehicles Test Procedure (WLTP). As an example, the limit for passenger cars is 93.6 g CO_2 / km with the target to drop to 49.5 g CO_2 / km in 2030 and finally to zero in 2035 (Union, 2025).

In the US the limits are based on Corporate Average Fuel Economy (CAFE) standards and the Environmental Protection Agency (EPA) regulations. Since 2021 the target for passenger cars has been 100 g CO_2 / km. In April 2024 the EPA published new targets such as 61.5 g CO_2 / km in 2030 and 45.4 g CO_2 / km in 2032 (Agency, 2024).

As introduced earlier, besides the emissions during vehicle usage, the vehicle production contributes to the overall CO_{2eq} footprint. In average the production of a small size vehicle with fuel consumption causes 8,700 kg CO_{2eq}, mid-size vehicle 10,800 kg CO_{2eq} and full-size vehicle 14,400 kg CO_{2eq} (Schwendinger, 2025, p. 3). The total emissions of a vehicle including production and usage sums up 30,000 – 60,000 kg CO_{2eq} for combustion engines. The CO_{2eq} footprint of battery electric vehicles (BEV) depends on the type of energy fueling the batteries during the use phase. By using renewable energy during the usage phase a small BEV reaches about 11,000 kg CO_{2eq} per lifetime, while for an electric SUV, the CO_2 equivalent can be twice as high. (Schwendinger, 2025, p. 4).

A small internal combustion engine (ICE) vehicle reaches lifecycle emissions of about 52-53 t CO_{2eq} as shown in Figure 2, while a battery electric vehicle (BEV) reaches significant lower emissions of about 11 t CO_{2eq}. The absolute values depend on different factors such as vehicle and engine size as well as the energy source for combustion engine fuel and electric energy. In addition, the assumed lifespan of the vehicle contributes to the absolute differences between ICE and BEV. As an example, a lifecycle carbon footprint case study comparing ICE and BEV vans in the United States of America demonstrates similar differences between both models as shown in Figure 2 for a vehicle lifespan of 150,000 km. A shorter lifespan of 100,000 km shows almost similar absolute emissions, while a longer lifespan of 350,000 km shows a larger difference between the emissions (Farzaneh & Jung, 2023). In literature the values vary around 20% based on the factors described. However, the most important aspects remain the same over the different studies and sources. About three-fourths of the lifecycle emissions of an ICE vehicle are generated during operations, while most of the emissions of a BEV are generated in the production phase caused by the resources required to produce the batteries.

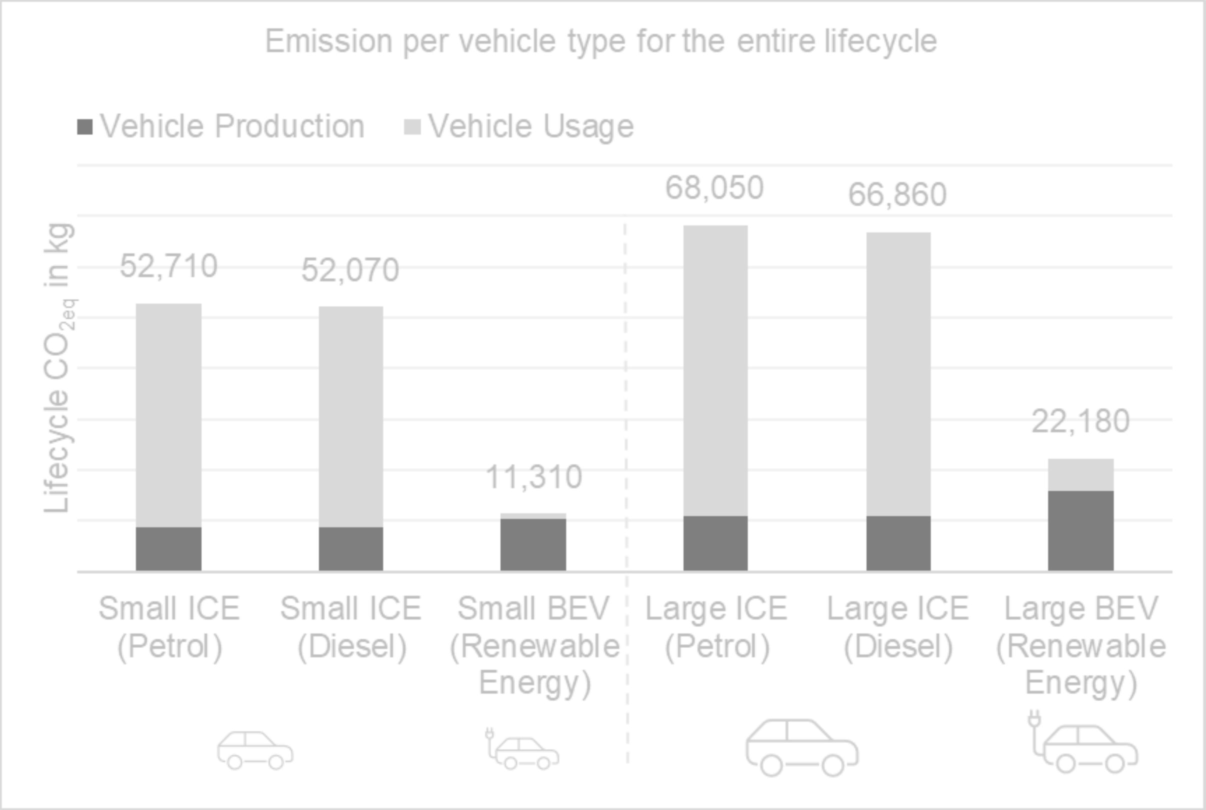


Figure 2 Emissions in vehicle life cycle based on VCÖ data (VCÖ, 2022)

The transformation of automotive industry from fossil energy towards electric energy powered vehicles will reduce the emissions during the usage phase of the vehicles, the technologies are available and state of the art. The present thesis proposes solutions to reduce the manufacturing emissions by evaluating methods to increase the efficiency of reused materials. Figure 2 demonstrates the significant impact of potential solutions to reduce the vehicle production emissions for battery electric vehicles. If parts of the about 10 t CO_{2eq} equivalent caused during the production phase can be reduced by reutilizing materials from former end-of-life vehicles, the CO_{2eq} footprint of the BEV will drop significantly.

2.2 Circular economy

The circular economy describes a closed loop resource flow model. The input of resources and energy as well as waste, emissions and energy leakages are minimized when the loops of material and energy are closed or narrowed in a regenerative system (Geissdoerfer et al., 2017). The definition suggests that products should be manufactured with the lowest possible amount of material and energy. When using the product there should be as little as possible emissions or waste of materials and energy by defective parts or disintegrated material. At the end of the product lifetime materials and energy should be reusable for new products, minimizing the waste and restarting a product lifecycle.

In the circular economy production processes, products as well as product consumption improve and develop constantly, therefore the circular economy is a dynamic process. An example for the continuous improvement is the technological progress of hardware in the digital industry resulting in the reduced need for resources (Hauff, 2023, p. 19). As the circular economy consists of a wide field of economical, ecological and social considerations, there are multiple gaps where research is required.

Despite different aspects and definitions of CE the following principles published by the Fraunhofer Institute in 2017 are mainly aligned within the CE research community (Hauff, 2023, p. 50):

- Reduce demand through circular use of raw materials
- Prolong product lifespan and reintroduce materials into the cycle at the end of use
- Optimize reuse, recycling, and product design to minimize losses in quantity, value, and quality of the product
- Prevent cycle losses through energy recovery and degradable substances
- Avoid components harmful to the circular cycle
- Minimize energy consumption to sustain the circular system
- Apply the concept across regions, industries, companies, and products

Different tools are described to achieve a circular economy. In the concept phase the product can be designed for a long product lifespan in contrast to design fulfilling the minimal durability requirements. The design can also consider repairability of wear components or a reuse of components after the lifespan. In the operation phase maintenance cycles can be planned to use the lifespan to full capacity. At the end of the product life, remanufacturing or refurbishing concepts can be considered for the product or its components. Material and parts that cannot be reused, should enter a recycling process resulting in a minimal waste of the end-of-life product (Geissdoerfer et al., 2017).

The different tools are summarized in one key concept of circular economy, the R-imperatives, which contribute to a clearer understanding of CE in operation. Reike et al. applies the term of retention option for the different R-typologies. Each resource has a certain elemental value which needs to be preserved as long and close to their original state as possible. This value retention with minimized losses can be achieved by the options shown in

Table 1 (Reike et al., 2018).

Table 1 Value Retention Options in CE (Reike et al., 2018)

Retention Option	R#	Description
Refuse	0	Refraining from producing and buying, less consumption
Reduce	1	Less consumption by longer use of products, product sharing
Reuse	2	Implementation of second lifetime, secondhand cycle, minor repairs of used product
Repair	3	Restoring the functionality of the product by repairing worn-out parts
Refurbish	4	Restoring the functionality of the product by replacing worn-out parts
Remanufacture	5	Restoring the functionality of the product by replacing key modules of the product
Repurpose	6	Create new products with old parts
Recycle	7	Converting waste materials into reusable raw materials
Recover	8	Energy generation from waste treatment
Re-mine	9	Extracting valuable materials from old waste

The R-typology can be found in various sustainability literature and visualizations and might include just some of the in

Table 1 listed options.

A strategy for retention options in mobility would be a reconsideration using the variety of mobility types such as sharing and public transport rather than the individual vehicle (reduce). Figure 3 illustrates the smart decisions between mobility options in the first third of the circle. Broken down to the individual vehicle efficiency, durability (reuse) and repairability (repair) should be increased. This can ensure an optimal utilization of material and energy according to the lifespan of the vehicle. It should be designed to be repairable, and a structured maintenance cycle is the baseline for a long vehicle life. The reconditioning of old vehicles (refurbish) can extend the lifespan by replacing old components with new technologies. Even a replacement of the engine and powertrain is considered by start-ups focusing on refurbished cars. In addition, the reutilization of parts in new vehicles (remanufacturing) or in new products with a different purpose (repurposing) can be a major step towards circular economy. As an example, typical components for remanufacturing in the automotive industry are turbochargers, steering systems, alternators, gearboxes and engines in small quantities or single batch processes (Steffen Butzer, 2016, p. 6).

At the end of the vehicle lifetime, material can be reused (recycle) to bring it back to the material cycle for new products. Materials that cannot be recycled, can be thermally used and transferred into energy (recover) (VCÖ, 2022). Figure 3 illustrates the retention options of the circular economy in mobility and transportation.

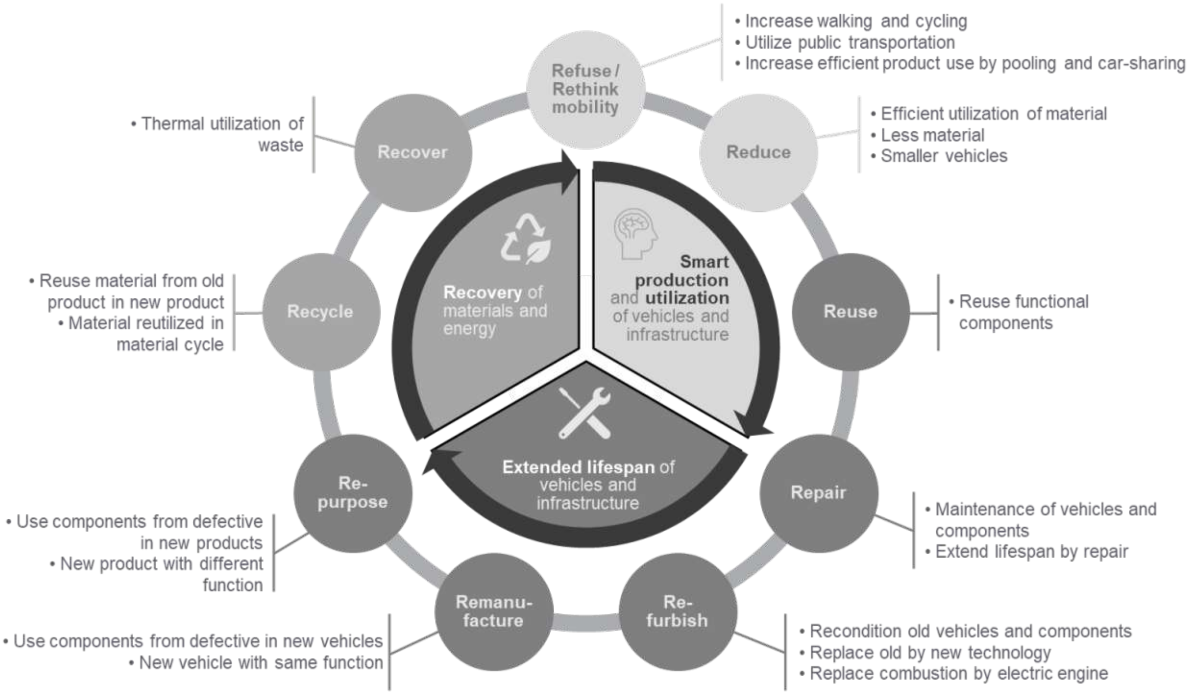


Figure 3 Retention options for circular economy in mobility based on VCÖ factsheet of circular economy (VCÖ, 2022)

According to the analysis of Michael Braungart and William McDonough in our industrial society about 90% of all materials for manufacturing goods are waste and about 5% of the raw material needed for manufacturing and delivering the good are contained in the product itself (Michael Braungart, 2014, p. 48). The numbers may have shifted slightly in the last 10 years according to awareness, regulations and technical improvements for product circularity. However, most production processes are still linear, producing waste from raw materials.

The European Green Deal includes the Circular Economy Action Plan consisting of initiatives that guide products and services into sustainability avoiding any waste. As an example, the product design should be improved to avoid short lifespans and end-of-life waste resulting in environmental damage. In another example the European Commission aims for the improvement of production processes towards circular economy. Therefore, emission regulations are reviewed based on the best available technology for minimal emission impact. In addition, the utilization of digital technologies to monitor resources is supported by the Action Plan. Symbiotic industries, industries transforming emissions from one branch into resources of the other, such as recovering energy from production processes, are supported within the certificate emission system. That are some high level examples of the Circular Economy Action Plan that should highlight the efforts on this topic (Hauff, 2023, pp. 70-72).

Regarding transportation, European Union (EU) regulations include circular requirements for new cars, end-of-life vehicle collection and treatment as well as the export of used cars outside of the EU. The latest proposal merges the directive 2000/53/EC on end-of-life vehicles and directive 2005/64/EC on the type-approval of motor vehicles regarding their reusability, recyclability, and recoverability. The proposal extends the scope from passenger vehicles to motorcycles, trucks and buses (Ragonnaud, 2025).

Based on the analysis of the European Parliamentary Research Service (EPRS) 286 million motor vehicles were on the road in the EU in 2022, and about 6.5 million vehicles reach the end-of-life status becoming waste every year. Considering that the automotive production represents about 19% of steel and 10% of total plastic consumption as well as 42% of the aluminum required just for the transportation sector, there is huge potential for material recycling and opportunities for CE in the automotive industry. It is also a required field of improvement for the EU target of climate neutrality by 2050 (Ragonnaud, 2025).

The regulations for circular economy motivate the automotive industry to consider circularity in vehicle production as well as the end-of-life vehicle (ELV) collection and treatment. However, as a matter of fact about 3.5 million ELVs disappear every year and with them valuable materials that could potentially be recovered in the next steps of the cycle (Azdad, 2025). Considering the ELV potential of 6.5 million vehicles, without export regulations at least 3 million ELVs could be included in the material circle for new vehicles or products. In the current state there are no regulation targets for the recycling of aluminum and steel, just feasibility studies to understand the capabilities and needs. In terms of plastic content new vehicles are required to consist of at least 25% recycled plastics by 2032, which should come from ELV dismantling and recycling. Besides the regulations, low recycling rates of materials are caused by the insufficient separation of materials. In the industry the targets for recycled steel grow to 30% in 2035, of which 75% should be contributed by ELVs (Azdad, 2025).

One of the specific drivers for the recycling targets is global material demand. The OECD forecasts a demand of 167 million tons of material in the year 2060 compared to 79 million tons in 2019 (Hauff, 2023, p. 31). Activities in circular economy can help to avoid this dramatic increase with the retention options refuse, reduce, reuse and, as discussed earlier, recycle.

In a systematic literature review on circular economy in the automotive industry Du et al. point out, that there are already multiple applications of CE introduced but not widely scaled. The authors identified the missing collaboration between different stakeholders of CE on the supplying and demanding side. Although the automotive industry cannot be fully circular, there are opportunities for academic research and identifying business models to implement CE (Du et al., 2025).

2.3 ELV disassembly

Based on research, the disassembly of a car body is not standard, but pilot projects are initiated and described in chapter 2.4.2. There might be multiple reasons that many automotive manufacturers and most automotive suppliers refrain from this part of the product lifecycle such as complicated market and logistic systems to return ELVs into the lifecycle, missing regulations and unknown business opportunities.

The global ELV recycling value is about $ 27.5 billion and is expected to grow to around $ 47.9 billion by the end of 2032. Main drivers are regulations reducing automotive waste and improving recycling efforts. According to the materials recovered, the metals are the biggest share and therefore have the focus in this industry. Secondly, plastics play a major role in recycling. Glasses are less valuable than plastics and metals but also can be recycled. Rubber, mainly from tires, has also a growing demand for recycled rubber products (Sharma, 2025).

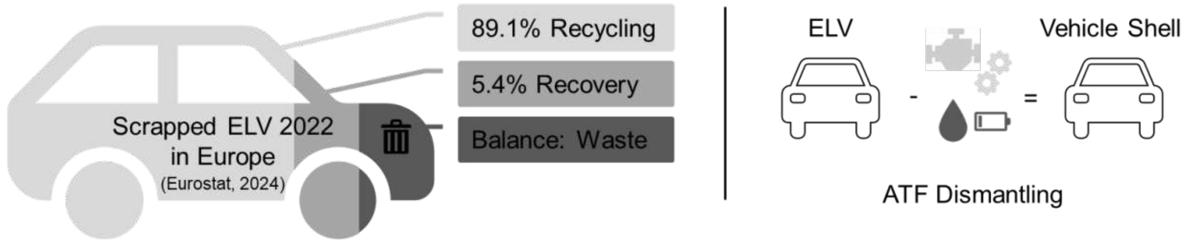


Figure 4 Recycling rate of scrapped ELVs in 2022 (Eurostat, 2024); vehicle shell after dismantling at ATF (Berzi et al., 2013)

The ELV potential of about 6.5 million vehicles per year in Europe mentioned earlier includes all brands, types and different manufacturing dates of passenger vehicles. In the year 2022 about 4.7 million passenger cars were scrapped in the EU with a total weight of 5.5 million tons. As shown in Figure 4 about 89.1 % of the material was recycled, and in addition about 5.4 % of the material was reused to recover energy (Eurostat, 2024). However, the recycled material is mainly used in different industries but automotive. For example, recycled steel shows higher copper content and therefore cannot be used in automotive manufacturing but is often used in the construction industry. To reuse metals in new vehicles, the purity of materials needs to be increased. The critical contamination of different elements such as copper and nickel is relevant for the flat-rolling process in steel production ensuring the required surface quality to be used in car body stampings (Froelich et al., 2007). A disassembling process can potentially improve the purity of the resulting materials (BMWGroup, 2024).

According to other elements, the authors of a life cycle assessment (LCA) of hybrid vehicle recycling conclude that the removal of just plastic parts and circuit boards from electronic control units does not show any significant environmental gain. The applied effort for the removal of those parts shows no significant benefit (Belboom et al., 2016).

Another relevant study about dismantling and interior disassembly in China analyses different approaches for the disassembly prior the shredding process. After dismantling the so-called fine disassembly approaches include electronic parts, powertrain and suspension and exterior parts but don’t include the entire wiring, some interior and any separation of the car body with the outcome, that the purification does not significantly change. The target of the study is the environmental and economic impact of different approaches such as automated and manual dismantling and fine disassembly. The greatest benefits show large scale and automated approaches with the focus on energy efficiency in all processes (Zhang et al., 2020). The results should also apply to additional disassembling processes as suggested in the thesis.

The shredding and sorting process is part of continuous improvement. Research and development of technologies in this field constantly improve detection and separation methods for different elements. A standard process and the material outcome are described in Table 2. While ferrous and non-ferrous materials can be easily sorted, the differentiation of non-ferrous outcomes such as different aluminum alloys require additional processes. Besides metals, other vehicle materials such as plastics and fabrics are considered as Automotive Shredding Residue (ASR) and not recycled (Soo et al., 2017). The Laser Induced Breakdown Spectroscopy (LIBS) can be used for the identification of different aluminum alloys based on the aluminum classification. In combination with artificial neural networks the reproducibility of the identification results can be increased based on the European project SHREDDERSORT (Campanella et al., 2017).

Table 2 ELV Shredding and sorting process (Soo et al., 2017)

Process Step	**Interim outcome**	**Recyclable outcome**	**Non-recyclable outcome**
Shredding	Shredded ELV		
Magnetic Separation		Ferrous metals	
Trommel Screening	Fine and coarse materials		
Eddy Current Separation (fine 0-50 mm)	Stainless Steels + Automotive Shredder Residue (ASR)	Non-ferrous metals	
Eddy Current Separation (coarse 50-200 mm)	Stainless Steels + ASR	Non-ferrous metals	
Sensor Sorting	Stainless Steels + small fraction ASR		ASR
Air Knife Systems		Stainless Steels	Remaining ASR

2.4 Cross industrial practices

Good practices described in this chapter reveal the opportunities and potential of circular economy. The different approaches in various industries might be valuable to answer the research question (RQ) with the focus on disassembly to increase the efficiency of material reutilization.

2.4.1 Battery disassembling and recycling

Battery recycling currently is one of the main focuses in the automotive industry. Based on the lower emissions of battery electric vehicles in their lifetime compared to combustion engine vehicles as shown in Figure 2, they play a major role in reducing the CO_{2eq} footprint in transportation and mobility. Therefore, the total volume of electric vehicles will continue to increase. The manufacturing of electric vehicles currently requires material resources with globally limited deposits. One of those materials is for example lithium with the biggest mining capacities currently in Australia, Chile and China (Review, 2025). In a difficult worldwide trade situation with increased tariffs and a growing demand from different industries for the same materials, circularity for battery materials contributes to reliable supply and process chains and economic products. On top of the economic considerations, the European Union issued in 2023 a regulation to increase material recovery rates, introduce transparency for recycling with the mandatory digital battery passport in 2027 and targets for ELV battery collection of 51% by 2028 (Union, 2023). This regulation motivates industries around battery recycling. In addition, the reuse of ELV batteries for different applications outside the automotive industry is an option to provide a second life to the battery. Following the principles of CE as described in chapter 2.2 research and development should focus on the extension of battery lifetime, optimized repairability and recyclability to extract rare materials for the next battery vehicle generation. That requires collaboration between automotive manufacturers and suppliers, including logistics, the product users, and the repair and recycling industry. Batteries need to be designed for circularity (Hauff, 2023, pp. 89-90).

The first examples of battery recycling were launched in the last three years. The automotive manufacturer BMW introduced a recycling system for electric vehicle batteries to reuse the raw materials in the BMW Brilliance Automotive Joint Venture in China in 2022. At the end of 2024 BMW together with the sustainability technology provider SK tes launched a similar system in Europe, where ELV batteries are shredded and raw materials such as nickel, lithium and cobalt extracted in a hydrometallurgy process. In addition, BMW will introduce the closed loop system into the North America region in 2026 (Schaidnagel, 2025).

Mercedes started a recycling factory in Kuppenheim, Germany, with a capacity of 2500 t which equals to 50,000 battery modules (VDI-Z, 2025a).

The automotive production integrator FFT investigated an automated production concept for battery recycling showcasing the potential for disassembly solutions for one component of the ELV. The identified challenges are manifold. Besides the variety of battery components, for example cell type, electrical characteristics and cooling, the variance of materials such as steel, aluminum, copper, rare materials, graphite and plastics is challenging for the recycling process. In addition, battery modules are protected and sealed with foam, wax and adhesive. In both the battery assembly and disassembly processes, managing the maximum applied heat is crucial to prevent damage to the battery. The concept of FFT contains an identification system of the battery module and its joints, and extraction of the cover with the choice of tools corresponding to the identified joint. A screwdriver releases screws and flow drill screws while gripper and lever help to dismantle adhesive bonded covers. The batteries are then discharged. Robot assisted but mainly manual processes follow to disassemble the modules, cables and electronic components before the batteries get automatically separated from the rest of the modules. The challenge to handle different battery systems in one production concept remains open for further development (Feik, 2024, p. 21).

The recycling approach for batteries is different from the disassembly of car bodies. However, some of the processes can be adapted into interior disassembly processes, and the challenges of the last example align with the challenges for an ELV disassembling due to the variation of products and therefore technologies.

2.4.2 Car manufacturers recycling approaches

The recycling industry technologies based on the process steps shown in Figure 5 are continuously improved to reduce costs, increase throughput and reduce the environmental impact. Innovations for automated dismantling systems emerge, utilizing robots to efficiently separate modules and parts. To identify materials more accurately, scanning systems such as spectrographs in combination with AI-based algorithms are introduced. Shredding technologies consuming less energy and producing fewer emissions by water-based shredding and cryogenic processing are in development to improve the CO_{2eq} footprint of the recycling process (Croft, 2024).

Some car manufacturers engage in the CE focusing on the design with recycled materials. Nissan recently presented the main issues for dismantling, e.g. the heavy-duty machinery, so called nibblers, deleting the ELV and destroying potentials for materials with high purity compared to a scrap material mix (Bito, 2024, p. 25). In current disassembly processes there are gaps in increasing the quality of the output materials. The approach to utilize more recycled materials in the car body design would require high efficiency in material recycling.

The Renault Group introduced the program “The Future is NEUTRAL” combining aspects of refurbishing, reusing and recycling materials from ELVs for the automotive industry. The subsidiaries INDRA recovers valuable parts and materials from accident-damaged cars and ELVs. Together with external partners another subsidiary Gaia focuses on remanufacturing and repairing electric vehicle batteries, engines and electronic parts. Batteries that cannot be repaired are refurbished for second life e.g. as energy storage in the renewable energy sector. The large-scale program from the Renault Group sources the majority of about 60% of the ELVs from individuals via pick-up service or insurance companies. The manual processed disassembly includes the dismantling of valuable parts for the reusage value stream as well as partial interior disassembling for pre-sorted material delivery to the recycling factories. Especially plastics are better presorted prior to the shredding process compared to process from dismantling to compacting and shredding as shown in Figure 5 (RenaultGroup, 2025).

Toyota Motor Europe (TME) has launched the Toyota Circular Factory (TCF) at its Burnaston plant in Derbyshire, UK, to process end-of-life vehicles with a focus on recycling, repurposing, and remanufacturing. The facility aims to reuse parts, remanufacture items, and recycle materials, contributing to Toyota's broader sustainability goals. TME plans to recycle around 10,000 vehicles annually, recovering significant amounts of plastic, steel, and other materials.

This initiative supports Toyota's commitment to achieving carbon neutrality in its facilities by 2030 and across its European product line-up by 2035 (JustAuto, 2025).

The automotive manufacturer Audi and the recycler TSR Resource started a feasibility study with about 100 ELVs that were dismantled, shredded and sorted to provide the material to the suppliers for new vehicles. The result shows that about 60% of aluminum and 85% of steel can be recycled and reused in that specific case. In the next phase Audi provides about one thousand of its pre-series models to the recycler TSR Resource. The recycled content is transferred to a virtual material account which can be used by the material suppliers, getting the recycled content from Audi via the recycling company. This pilot project can be a model for the entire Volkswagen Group and shows how material cycles can be closed (Volk, 2025).

In another example, the manufacturer JLR revealed a 26% CO_{2eq} emissions reduction in production of the product by utilizing upcycled aluminum, an alloy from ELV scrap and household aluminum scrap. In the manufacturing process the alloy is constantly tested to meet the specific requirements for the product (JLR, 2020).

In the disassembling and recycling center of the BMW Group mainly prototypes follow the dismantling and disassembling process to extract engine and transmission parts, seats and the main interior. In a single process the wiring harness is torn out, one of the key elements causing the steel contamination with copper when shredded as part of the car body. BMW wants to create knowledge along the disassembling for improving recyclability as well as future design aspects for circularity (BMWGroup, 2024).

2.4.3 Applied research and development

The research project ZIRKEL from Fraunhofer IWU aims to reshape the production of electric mobility components focusing on design for circularity. Components, parts and materials can be reused, refurbished or recycled with minimal loss of properties and quality. The challenges of disassembling and recycling when lacking manufacturing standards and finding similar joining technologies should be overcome by the development of an automated disassembly process. First, part conditions are analyzed with vision systems supported by AI algorithms. Parts are then separated and sorted for reuse, remanufacturing and recycling processes. Beside the comprehensive strategy for the analysis and automated disassembly, methods and guidelines to improve circular economy for electric engines are the targeted outcomes (Schmidt, 2024).

In another project EKODA Fraunhofer IWU focusses on damaged cars and the recovery of usable components. Similar to ZIRKEL the part condition is evaluated in a dynamic process to guide the disassembly process and carefully separate components until the part can be recovered for reuse or remanufacturing (Schmidt, 2025).

Within the scope of the European Union project CarE-Service the reuse of ELV material as a new vehicle component is analysed. As an example, from an ELV roof a piece of steel sheet can be cut out and reused in another simple forming process for a new car body part. As the forming process changes the material properties of metal sheets, ELV components with just slightly forming shapes could be reused. Extracted material should also consist of same gauge and material characteristics of the desired part (Haase, 2025).

Some of the car body components may contain synthetic materials for required functionalities in which metal assemblies have limited performance. One of the examples would be parts for acoustic insulation added to hollow structures of the assembly. Design engineers simulate and modify the noise, vibration and harshness (NVH) of the components to fulfill specified requirements of the customer. Another example is adding synthetic ribs and structures to increase component stiffness. The hybrid material structures require special attention in the disassembling process and methods need to be studied to extract the synthetic materials from the metals to increase the purity of the metal in the disassembling process.

The synthetic materials can be recycled in a mechanical process. Disassembled components are collected, sorted, shredded, cleaned and smelted. In the process the identification of the materials is important to increase the quality of the recycled material, which is studied in the spectrographic research project in recycling of synthetics “SpecReK” by BASF, Endress+Hauser and TechnoCompound utilizing cutting edge measuring methods combined with artificial intelligence (VDI-Z, 2025b).

2.4.4 Collaboration and partnership

The Automotive Circularity Platform (ACP) as an example for a comprehensive approach of circular economy (CE) is a project initiated by material suppliers that aim to cover the entire automotive recycling chain, car-to-car. The ACP suggests the EOL product enters the dismantling process from recycling organizations, followed by enrichment from the steel companies to close the cycle to manufacturing and the OEM (Thyssenkrupp MX, 2024, p. 4). Automotive suppliers do not seem to be part of the remanufacturing process in this model. The question arises whether they should be involved as one of the contributors to the manufacturing process. In general, the platform demonstrates that circular economy in automotive is a collaborative approach and partnerships can help to improve the efforts.

The car manufacturer Toyota aims to establish a network of ELV dismantling facilities worldwide as part of the Toyota Global 100 Dismantlers Project. In October 2024 Toyota endorsed the En Tsumugi ELV Dismantler Corporation in Mexico, which is in Southeast Asian region the fourth endorsed dismantler following similar facilities in Thailand, Vietnam, and Malaysia. The project promotes proper dismantling facilities to improve the environmental challenges of ELVs (Toyota, 2024). In Europe, Toyota set up the first model facility with the Comet Group in Belgian within the scope of the project. As a first result of this partnership the dismantling of a fuel cell electric vehicle could be demonstrated and a video manual was created (Toyota, 2025).

2.4.5 Beyond the automotive mindset

In the sustainability report from 2024 INNIO stresses beyond different advanced technologies and services its remanufacturing process. The group expands the portfolio of reconditioned parts to offer their customers an end-of-life emission reduction as well as lower investment. INNIO is an energy solution and service provider offering Jenbacher power generation and compression technologies. Among resilient supply chain and manufacturing, and responsible operations and social responsibility, low-carbon and circular products are one of the three strategic pillars for sustainability. INNIO points out the maintenance, reusage, refurbishment and remanufacturing as well as shared products as part of their group’s circular economy strategy to reduce the systematic waste of materials. The report shows a recycled material content of 58% for the products (INNIO, 2025). The INNIO group introduced a five steps process for remanufacturing. The first step is the disassembling and cleaning of the engines and parts by skilled operators. In the next step disassembled parts are tested by following customer specifications. The worn parts and parts that do not meet the specifications are replaced and the engine is assembled. The quality assurance contains 100% testing and documentation of all assemblies before they get painted, packed and shipped. An entire engine can be overhauled, or core parts such as cylinder heads, bypass valves, intercooler, and oil pumps are remanufactured. There are no technical differences between overhauled “reUp” engines and new engines or remanufactured “reUp” spare parts and new parts. The processes are established for the entire product portfolio in all INNIO groups (INNIO, 2021).

In the railroad industry trains are designed for a long-lasting lifecycle and repaired or refurbished along their operations. The “ÖBB Technische Services GmbH” (ÖBB-TS) manages maintenance and repair of about 20,000 trains and 9,000 components. About 90% of modern trains can be repaired and 700,000 components were repaired by ÖBB-TS in 2024. For components that rarely fail in operations there are usually no replacement parts, so in a pilot project a 3D printed part replaced one of those failed components. The project shows the potential of additive manufacturing compared to a stockpile of service parts. Another aspect is the condition monitoring of the vehicles during operation to schedule and manage maintenance or replacement especially for wear parts such as wheels and brake systems (ÖBB-TS, 2025).

To summarize this chapter, there are various interesting approaches in different industries and research areas. The different experiences can help to shape circular economy across industries; some specific examples are relevant to the topic and research question of this study.

2.5 Gaps in automotive industry

The automotive industry optimized their full linear production concept over a period of about one hundred years from the raw material to the finished product including maintenance services during the usage of the product. The missing part of the product life cycle begins when the vehicle lifetime ends. Anything between the end-of-life vehicle and the reusage of its materials is not yet standardized or optimized although most of the ELV materials are recycled and used in different industries as the following chapter will show.

Figure 5 illustrates the usual ELV recycling process described by Berzi and commercial websites for used car parts. After the deregistration, when the vehicle is wrecked, first the fluids, batteries and other hazardous materials are removed. Those process steps are done at an authorized treatment facility (ATF). During the dismantling process some parts such as engines and alternators might hit the secondhand market, while tires, some plastic interiors and glass are removed for material recycling. The rest of the car is pressed into transportable blocks for compact transportation to a recycling facility. The compact car body block then gets shredded, and the material is sorted in different processes. The separation processes continuously improve in terms of the identification of the objects, separation methods such as magnets, air nozzles or mechanical pushers, and finally the overall process speed to gain as much material per minute as possible. The common outcome is sorted materials in steel and non-ferrous metals such as aluminum, as well as plastics and the shredder light fraction containing the rest of the mixed materials. The metals can be recycled. The rest of the material will be thermally utilized for energy recovery (Berzi et al., 2013); (Jürgen Sutter, 2025); (Autoparts24, 2025).

A study on the recycling process of a vehicle door on the Australian Recycling Industry identified that from the shredded material mainly, the steel is recovered and returned to the steel mills. However, the increased multi-material design and usage of plastics and composite materials reduces the yield on metal recovery and introduces the challenges of separation (Soo et al., 2016).

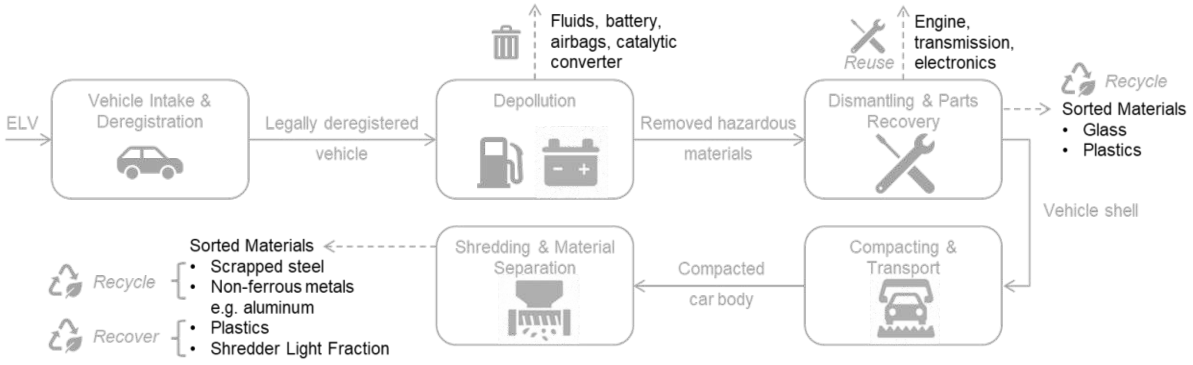


Figure 5 State of the art ELV recycling process (Berzi et al., 2013)

One of the key topics between the end-of-life and the material reusage or recycling is the disassembly of the vehicle. The main activities of research and development in this area is the product design for disassembly, the process and system design for disassembling strategies and technologies as well as automation levels. (Jovane et al., 1993).

In product design it should be considered to avoid the fusion of materials, especially of dissimilar materials. In a fusion joint the parent materials are transferred from the solid to the liquid phase by heat and sometimes pressure with or without additives to create the joint between both parts. These welding processes aim to have similar characteristics between the fusion zone and the parent materials, which is a challenge for any separation processes. Targeting sorted materials, the joint between materials is crucial to understanding and designing the separation process. In a study focusing on the dismantling and recycling of non-metallic parts of the ELV, the authors suggest a detachable product design, for example a modular design with joining elements that easily connect and separate the modules. In addition, hybrid parts e.g. metals with embedded plastics that make the disassembly difficult should be avoided as mentioned earlier. In general, mechanical joining methods are recommended by the authors to reduce complexity and difficulties in the disassembling process (He et al., 2021).

Besides design, another gap relevant for this thesis would be the information about the product details such as materials, joining processes, joint design and position. Currently, the manufacturer of the subassemblies owns the information and, because for missing digitalization and security concerns, information is not shared (Du et al., 2025, p. 9).

Digitalization plays a major role for the mentioned required data to efficiently follow the circular process. Data helps to prolong the lifetime, and data is required to close the material loops (Hauff, 2023, pp. 120-125). Currently ELVs don’t have detailed data, for example for the materials and joining processes to support any disassembling or recycling process. Digital product passports similar to the soon required battery passport can help to optimize efficiency of the next process steps.

To provide the comprehensive picture, the other gaps identified by the authors are organizational gaps, societal awareness and acceptance, regulations, quality of remanufactured products, quantity of returned products and specific battery related barriers (Du et al., 2025, p. 9).

3 Methodology

In this thesis different methods were chosen to answer the research question. Figure 6 shows the high-level overview of methods, sources and brief key results.

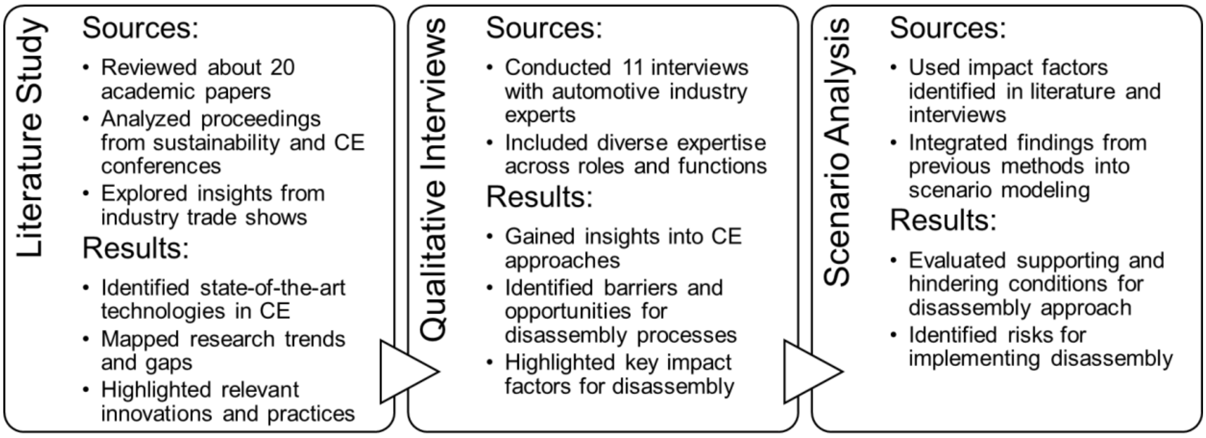


Figure 6 Used methods and results in the thesis (created by the author)

3.1 Literature study

The narrative literature analysis was chosen to synthesize existing research and identify gaps. From the search results for keywords around end-of-life vehicle and circular economy about 20 relevant papers and studies were selected to contribute to answering this thesis. The papers were published in the chosen timeframe of the last 15 years, and the majority was published within the last 10 years. The one exception about design for disassembly published in a journal in 1993 was chosen according to the high relevance to the research question. In addition, the search for press releases about recycling approaches in automotive, explorations about latest technology research with relevance to the topic at industrial trade shows such as the “Automatica”, Munich 2025, and the conference “Sustainability in Product and Production Engineering” by the Automotive Circle, Bad Nauheim 2024, provides a comprehensive analysis of the industry and research landscape. The flexible structure between academic and industry sources compiles the latest research contributing to the thesis. Therefore, the narrative review as a qualitative method in contrast to a highly structured systematic review was chosen.

3.2 Qualitative Interviews

The thesis includes the methodology of qualitative interviews to get a comprehensive view on the status, potential and especially the challenges for a car body disassembly. Different stakeholders along the vehicle lifecycle discussed questions about technologies, sustainability as well as business opportunities and requirements. The target of the interview is to identify the status of the circular economy in automotive industry, the potential and conditions needed as well as collaboration to investigate into car body disassembly.

To gather information semi-structured interviews are performed. Semi-structured interviews provide a comprehensive and detailed collection of data for a specific topic and are often used in qualitative research (Mayring & Gläser-Zikuda, 2008). With the combination of structure and flexibility the interview allows to generate new aspects based on the interviewee’s experience and creates an open environment for discussion between interviewer and interviewee compared to strict structures interviews (Qu & Dumay, 2011).

The interview contains questions relating to the technological, sustainable, and economical aspects of the research question. All interviews of about 60 minutes each were held online, recorded and transcribed for qualitative analysis using Microsoft Teams version 25198.1109.3837.4725.

The interview and the questions follow the structure of the three main stages. The opening contains questions about the general understanding of circular economy and touch points with the topic. The actual interview leads through the earlier mentioned three blocks and the debriefing allows for comments and some outlook into the future (Brinkmann, 2023). The questionnaire contains 24 questions and can be found in the appendix 8.1. The interview partners were selected among stakeholders of the vehicle lifecycle. Besides different professions from the automotive supplier industry, car manufacturers, material suppliers as well as machinery suppliers were selected. Table 3 shows the different experiences of the interviewees.

The interviews are analyzed to provide the findings based on the research question. To extract the key findings of the transcriptions and identify similarities discussed in chapter 5.1, Microsoft Copilot Pro was used (Microsoft, 2025). Since the transcripts of each interview contain between 25 and 35 pages, the analysis is interpretive and not mechanical as Brinkmann suggests (Brinkmann, 2023).

Table 3 Industry branch and experiences of qualitative interview partners (created by the author)

Industry branch	**Interviews**	**Region**	**Expertise**
Automotive manufacturer	2	Europe	Sustainability, Recycling
Automotive supplier	1	Europe	Sustainability
Automotive supplier	1	Europe	Business Development
Automotive supplier	2	North America	Product Development
Automotive supplier	1	North America	Process Development
Automotive supplier	1	Europe	Strategic Management
Automotive integrator	1	Europe	Battery Disassembling
Material supplier	2	Europe	Sustainability, Recycling

3.3 Industry and scenario analysis

In addition to the identified gaps in chapter 2 the interviews indicate multiple challenges considering a car body disassembly. In a scenario analysis different technical, social and economic circumstances are reviewed to identify the scenarios supporting and hindering the potential for a car body disassembly that improves the circularity of ELV material.

In the first analysis the key drivers based on different aspects are identified in a macro-environment as well as in a micro-environment. The results of the analysis are the baseline to create scenarios in multiple future forecasting. The target of this chapter is the comprehensive understanding of the key factors that indicate a business opportunity for the ELV disassembly process prior to the shredding process.

A strategic tool to understand the external macro-environment that can impact the opportunities of disassembling is the PESTEL framework, which is an acronym for the different environmental factors: Political, Economic, Social, Technological, Environmental and Legal. Each factor is analyzed to identify different aspects of the specific industrial area. Based on the design it includes not only market but non-market factors too, which need to be considered for a comprehensive strategy. The outcomes are identified risks and opportunities from external forces that cannot be controlled but can be prepared for. The target is the determination of key drivers for change (Whittington et al., 2023, p. 64). To perform the PESTEL analysis, the macroeconomic factors of the next defined period are analyzed.

While the PESTEL analysis focuses on the industry, the Porter's 5-Forces tool dives into a particular enterprise or business to understand the competition and balance of power

(Williams, 2012). In this study the business is disassembly, and it is assumed that an automotive supplier would introduce the process and potential business. Currently, this analyzed disassembly process is not present in industry, so the 5-Forces analysis will determine potential and threats within the competitive environment (Porter, 1980).

Both industry analyses are the baseline to perform a scenario analysis. The scenario analysis helps to visualize complex uncertainties in a structured way. Based on the identified challenges and opportunities in chapter 5.2.1 the scenarios shall highlight the potential future path and impact. For the scenario analysis the 2 x 2 matrix method is used. Inspired by the scenario planning pioneer Perre Wack, who introduced those methods at Shell in the 1960s, the matrix was introduced by Peter Schwartz and Jay Ogilvy in the 1990s. The desired outcome would be the test of strategies for multiple futures to be prepared for critical uncertainties (Chermack, 2022). The scenarios help to understand the development of the environment in different alternatives of the future. To build a scenario first the scope of an industry or region is defined. The PESTEL analysis mentioned above identifies the key drivers for change. Those drivers are the baseline to develop different scenarios based on the main conditions of uncertainty and impact. As a result, the robustness of the current or desired strategy can be checked with the built scenarios. In addition, main indicators of each scenarios for a possible future can be identified to constantly observe the environment and maintain the ability to timely adjust the strategy (Whittington et al., 2023, p. 79).

4 Research design

4.1 Research question

This thesis suggests the introduction of a disassembling process as shown in Figure 7 to separate and sort materials instead of shredding the mixed material and accepting material contamination. The illustrated lifecycle phases in Figure 7 are described in chapter 2.5, the suggested disassembly starts with the vehicle shell from the ATF at the end-of-life stage displayed in Figure 4.

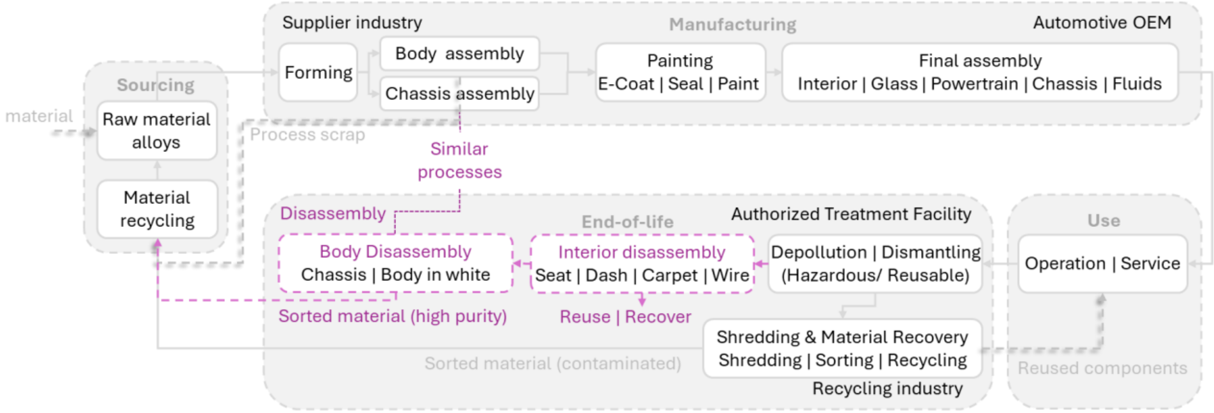


Figure 7 Vehicle lifecycle and highlighted focus of the master's thesis (created by the author)

There might be similarities between assembly and disassembly, so that technologies can be shared and complement the existing experience of stakeholders in the automotive industry. Besides technological aspects the thesis aims to examine key economic and ecological factors for establishing a disassembly concept.

Considering the state-of-the-art described in the background chapter 2, the following research question shall be answered:

"How can the implementation of end-of-life vehicle disassembling contribute to a closed loop vehicle lifecycle by recovering materials, focusing on the following details:

RQ1. Which existing assembly **technologies** may be utilized for the disassembling process?

RQ2. What is the **sustainability** potential of end-of-life vehicle disassembling regarding the carbon footprint reduction of the manufacturer's products?

RQ3. How can the end-of-life vehicle disassembling be **economical** beneficial?"

4.2 Research scope

The disassembly process in the context of the research question is the procedure of the separation of the vehicle shell to a certain level of components which consists of materials that efficiently can be recycled. The vehicle shell shown in Figure 4 is the outcome of the dismantling and depollution process from the ATF shown in Figure 7. It consists of the car body, mainly made of metals and interiors such as seats, carpets, dashboards and covers, mainly made of plastic. For this thesis it is the interface to the suggested and studies process. The desired outcome are materials that are sorted and clustered beneficially for recycling. To limit complexity the thesis does not take the recycling potential from components such as seats, the interior or wire harness into account. The interior disassembly and the removal of wire harness and seats are considered as necessary process step prior to the car body separation into the desired metals.

4.3 Research approach

Existing technologies and approaches from the automotive industry as well as outside the automotive industry demonstrate potential and might be transferable for the desired approach of this thesis. Some of those approaches are discussed with the experts in this area during the qualitative interviews. The outcome is summarized and structured in the three fields of the research question: technology, sustainability and economy. The focus is on the drivers and concerns for a disassembling process.

Based on the outcome the scenario analysis describes the disassembling approach in multiple potential futures. This analysis helps to identify the key drivers supporting and challenging potential business.

As a result of all analyses, the technical and economic feasibility as well as the sustainability opportunities are described and concluded. Potential identified gaps in research should help to outline future investigations.

5 Results

The data analyzed based on the methodology of the thesis is presented and described in this chapter. First, the interviews are summarized for each of the three sections: technology, sustainability and economy. Each section highlights the main aspects contributing to the topic of the thesis. Another subchapter describes referred examples by the interviewees for best practices according to circular economy, which adds interesting aspects besides the three sections. Table 4 recaps the key outcomes of the interviews. The outcomes feed the scenario analysis with the main factors and their widely seen impact. As a result of the multiple future forecasting the risks and opportunities and their main impact factors are identified. A business evaluation checks the economic potential of disassembly, while a sensitivity study highlights key factors and relates them to the results of the scenario analysis. The combination of the different analyses should reveal the main impact factors for a disassembly strategy.

5.1 Qualitative Interviews

5.1.1 Technology aspect

The automotive manufacturers and suppliers are predominately using Resistance Spot Welding and Gas Metal Arc Welding methods for the car body and chassis assemblies. Mechanical joining methods like riveting, clinching and bolting appear across specific components such as doors and battery trays. Adhesive bonding is found in all components and for battery packs and interior joining this method is very common. In the interior, different plastics are glued which complicates the separation for disassembly and reduces the potential for recycling. Reflecting on the different joining methods, most interviewees agree that many technologies are not designed with disassembling in mind. The main requirements for assembled components are strength performance, rigidity and crashworthiness. These requirements dominate the decision for the joining method over any end-of-life considerations. The following quote given by an interviewee from an automotive supplier with automotive manufacturers as customers highlights the dependencies when choosing materials and joining methods:

“We also have very little influence over the materials used, because at the end of the day, it’s all crash relevant. The whole thing has many other requirements that within our small microcosm […] we simply can’t assess or influence in terms of quality. Essentially, we have to comply with the customer’s specifications, and in the end, it's the customer who has to ensure that they can trace it back properly” (anonymous interview, July 2025).

The first differences in opinions between the interview partners occur when the discussion turns directly to design for recycling. Automotive manufacturers show early efforts towards design considerations for circular economy while suppliers mainly rely on designs from manufacturers. The main challenges are seen in multi-material structures that hinder automated or clean disassembly processes. Prominent examples are steel and aluminum as well as multi-plastic hybrids. Another challenge is the use of advanced and ultra-high strength steel alloys which can be difficult for separation or even shredding processes. Press hardened steels currently achieve strengths up to 1500 MPa while the next generation with strengths higher than 2000 MPa is introduced. Separation and processing operations need to be designed considering those types of steel, and the worry about the wear of separation machinery was mentioned in one of the interviews. The same example was used to discuss the lack of information, labeling or metadata about materials and joining methods complicating the recognition and therefore the separation processes.

“Our key question: what can the dismantler actually do today? And what do they need to improve? Digital material and joining data, embedded in product labeling, could bridge the gap between car design and recycling reality” (anonymous interview, July 2025).

At the same time fusion joining methods used for joining steels as well as similar aluminum alloys are considered favorable for recycling. The welding process requires no or similar filler material, so that the materials do not need to be separated at the end of life and can be recycled as welded assemblies. In contrast, joining methods with elements that are different from the parent metals can cause problems in the recycling process. One given example is self-piercing riveting (SPR) that mechanically joins aluminum parts as described in chapter 5.3.6. For aluminum joints aluminum rivets can be used if the strength of the rivets is sufficient for the joint. For higher requirements and aluminum to steel joints, steel rivets are widely used. In a separation process, the joining flange can be cut on the aluminum side to maintain its purity. The leftover aluminum contamination and the rivets on the steel side could remain up to a certain percentage. Aluminum content in scrapped steel is no problem for the recycling process while aluminum should be kept free from steel contamination.

Digital product labels, including material and joining operations, are seen as an opportunity as mentioned earlier. The battery passport is one example for a regulation in this field. An interviewee emphasizes the improvement of the battery disassembling:

“Transparency and traceability are the key enablers. The upcoming battery passport — showing materials and joining techniques — will be a game changer for the industry” (anonymous interview, July 2025).

A challenge for the automation of ELV disassembly is the variant complexity considering different brands, models and even model years within a timespan of about ten to fifteen years. The utilization of camera systems and AI is discussed to deal with the complexity. Even with recognition of the ELV details the understanding of vehicle design and joining technologies is seen as crucial for a clean separation process. Additional challenges occur by aged materials, corroded or damaged parts. Even if the technical hurdles can be solved with technically advanced systems, investment is required which impacts the economic viewpoint.

An opportunity to enable circularity is seen in vehicle architectures with modular component concepts. Modules can be disassembled easier. If the modules consist of similar metals, those could be recycled without any further separation effort.

5.1.2 Sustainability aspect

Only a few companies track the CO_{2eq} emission footprint of their products in a structured way. From the interview partners it applies mainly to the vehicle manufacturers. Automotive suppliers rely on common databases to calculate their equivalents. In addition, for some products the manufacturers provide estimates or targets.

According to scrap sorting and material recovery most stamping shops collect and sort their aluminum and steel scrap to provide it to recyclers for reusing this pre-product scrap. The sorting of different aluminum alloys is also state of the art and common in most press shops. When it comes to the sorting of post-shredded material, the sorting process is also state of the art but often fails to meet purity standards, which is mentioned by the interview partners with expertise in the recycling area. Besides the metals an interviewee supposes:

“Everything else that's inside the vehicle — plastic, carpet, all that stuff — I’d say we probably don’t recycle it” (anonymous interview, July 2025).

The recycling of plastics is described as difficult due to compound formulations with low demand for sustainability, lacking the push for innovations to find solutions.

An important factor is the transportation of ELV and scrap components between the different stakeholders. The aspect of regional and localized recycling loops is discussed. As an example, in the construction works of a street, the old layer of asphalt is removed and shredded directly at the construction side to create the baseline layer for the new road. This optimal circle does not require any logistics. To transfer this example to the automotive sector, the installation of regional disassembling locations rather than centralized bigger plants is seen as a viable option for sustainability improvements.

Besides logistics within Europe, the supply chain is mentioned in multiple interviews and strongly emphasized in one of them. ELV materials should be kept withing the European recycling loops to support local economies and environmental goals. Exporting of scrap materials outside of Europe is viewed as a major barrier to circular economy. The ELV regulation approach from the European Union plans to fully automate the vehicle export checks to minimize the loss of ELVs and their valuable materials (EU, 2025). However, currently many vehicles are missing as described in chapter 2.2.

According to the CO_{2eq} emissions footprint described in chapter 2, the utilization of recycled material instead of raw material would improve the total footprint of vehicle manufacturing as the recycled materials currently bring in zero emissions. Just if raw material is required to upgrade recycled alloys the added material counts for some emissions. This can improve the product emissions footprint. To enable this benefit, more of the recycled materials should be reused in vehicles and the current reasons against this approach such as vehicle requirements are discussed in the technology section. On the part of the automotive manufacturers some material alloys with greater tolerances of impurity are explored to identify more areas for the utilization of recycled alloys.

The current vehicle design is seen as a barrier for disassembly. There are rare considerations for the separation of materials as already discussed in the technology section, but the topic is still seen as underprioritized. The design of various metals into the assembly results in a consideration of disassembly for recycling improvements. A mono-material approach would make the disassembling process obsolete. However, during the design phase the end-of-life challenges are rarely investigated. Design of current vehicle projects would require us to think about recycling in the future. One of the interviewees formulated this thought as follows:

“When you're building a car today, it's somebody else's problem after it leaves your lot, […] it's the 20 years from now problem” (anonymous interview, July 2025).

That is one reason why most interview partners don’t experience those design considerations and mainly interviewees from the automotive manufacturers underline their target for a design for recyclability. Especially the simplification of vehicle architecture and the integration of recycling-compatible fasteners and materials are mentioned to achieve this target.

Regulatory requirements for using similar materials that support recycling processes, and the material purity can help to improve the circular economy. The battery legislation is mentioned as one example. In general, industry-wide standards for recycling or traceability are seen as a huge opportunity. The European goals for recycling and emission reduction underpin the importance of localized recycling. In contrast some of the interviewees suppose that the technical capabilities to recover all potential ELVs are present but not utilized due to the ELV exports.

5.1.3 Business aspect

During the discussion about the economic benefit, most of the interviewees see challenges in this field and are under the assumption that the costs for disassembly are higher than the value of the scrapped material. Examples from the dismantling processes which are highly manual processes are transferred to the vision of interior and car body disassembling. The variant diversity of ELVs in models and brands are found as a reason for the highly manual process.

Manual processes are seen as too expensive to create any reasonable business. So, automation, which is seen as highly challenging, would be the key for a profitable business:

"It's important to push technologies — primarily to extend the end-of-life of products as much as possible, and to manufacture the products we need using as few raw materials as possible. Because when it comes to recycling, if we're doing it in-house, it has to work with minimal manpower. We see this frequently in production: as soon as you need a lot of manpower, it becomes very difficult to maintain cost-efficiency" (anonymous interview, July 2025).

Another aspect is the usage of recycled materials in new vehicles and their prices. Recycled materials are seen as more expensive than virgin material because they are produced in low volume with high processing costs. The question arises whether an added disassembling process to the circle adds more value than costs as one interview example points out:

“How do you make sure that when you go through the disassembly, every piece you take apart has value and is not just thrown away to get to what the one thing is you want? That […] is the biggest hurdle because it's going to be expensive to do it […] you have to get every bit of value out of every part you take off that car” (anonymous interview, July 2025).

One of the interviewees highlighted the lack of empirical data on the material recovery value from a disassembling versus the shredding process which would be a baseline for further economic discussions. The shredding followed by advanced sorting is seen as less precise but economically viable at scale.

An example of an internal closed loop was brought by several interviewees from the automotive suppliers. Aluminum casting that are defective after the casting process are remolten to create new material for the ingots that are processed again to create new products. That prevents material losses creating a closed material loop.

On a strategic level suppliers and manufacturers agree that OEMs must lead the sustainability activities with mandates, incentives and shared platforms to support a cross-industry collaboration. Some of the examples are described in chapter 2.4.2. Another key strategic leverage is regulations such as end-of-life laws or the battery regulations mentioned earlier. Consortia or hubs involving automotive manufacturers, suppliers and recyclers are seen as an enabler to align on standards, specifications and material flows.

“What you often see is that every company tries to optimize within its own processes, and even within departments, it’s often limited to what's considered their own responsibility — collaboration beyond that is rare” (anonymous interview, July 2025).

The quote illustrates how industry today is seen to work in silos also to protect potential competitive advantages. A collaborative approach would require a cultural transformation across the industry.

As an outlook for business models the interview partners stress out the importance of balancing material recovery, sustainability and cost-efficiency. To evaluate the profitability of disassembling the recovered material quality, the compatibility to different vehicle brands and models and the processing costs of technology, labor and logistics are identified as main factors. Any investments into circular design as preparation for disassembling processes to improve recycling needs to be justified. Long-term sourcing contracts for the ELV, the scrap and the recycled materials are mentioned as options to support the potential business.

5.1.4 Circular economy best practices

Especially in the battery sector the development is seen as a good pilot to learn from. The battery passport concept inspires a broader circular approach by tracking components, materials and the needs for disassembly. In one interview some of the regulations are criticized as too strict, debilitating circularity. For example, the transportation of battery tray components is required to be treated as hazardous material which requires special treatment increasing the logistic costs. The overall approach of regulations is seen as a huge support for circularity, but the industry should be involved in creating practicable standards. Another example for circular economy is the repair of batteries from battery electric vehicles. Specialized repair clinics demonstrate how to remanufacture damaged batteries to extend the lifetime and keep the material in operation.

A further example brought by one of the interview partners is the scheme for smartphone returns. Returned products are manually torn down to recover the highly valuable materials. In addition, discount rates motivate customers to keep the phone longer, extending the product lifetime. This approach might be a potential model to motivate vehicle owners by keeping the product longer or returning them for responsible recycling by tax rate discounts, refund systems or compensation.

Back to automotive an alternator deposit system is described and praised for its circular approach. The automotive parts are collected, refurbished and resold. That guarantees both economic and sustainability gains. In shipbuilding and aerospace, the remanufacturing and reuse of components is common to extend the lifecycle of assets.

Besides the product, reusable systems for logistics are mentioned by multiple parties. Modular system racks and reusable dunnage systems can help to prevent waste from transportation.

5.1.5 Summary qualitative interviews

The key takeaways of the interviews for each section of the research question are compiled in Table 4.

Table 4 Summary of the qualitative interviews (created by the author)

RQ aspect	**Key result**
Technology	• Vehicle design centers on performance, not disassembly • Modular and mono-material design could serve disassembly concept • Challenging separation of mixed materials, elements and combinations with ultra-high strength steels • Lack of traceability, e.g. product passport • Complexity of ELV variants
Sustainability	• Utilization of recycled material helps reduce emissions footprint • Emissions from logistics and transportation to and from disassembly should be considered • Regulations e.g. for recycling targets could boost disassembly approach
Economic	• High costs associated with disassembly processes, especially in manual operations • Recycled materials for vehicle utilization are usually more expensive due to current low production volume • Lack of data on recovery value for disassembly versus shredding process
Best Practices	• Deposit models seen in other industries could be considered for vehicles with the challenge of an about 15 years timespan for return

5.2 Scenario analysis

In this thesis a timespan of about five years is chosen to analyze the industry for certain impact factors. This timeframe has predictable attributes based on the current trends and development in different areas. Longer time periods add more assumptions and blurriness to the analysis; however, the results can show the main impacts based on different factors which are potentially still applicable in the long run.

5.2.1 PESTEL industry analysis

Based on the research in chapter 2 and the interviews in chapter 5.1 the main aspects for each factor are identified and summarized to the main three to five aspects per factor.

Table 5 shows the aspects which can influence the business of the automotive industry with the focus on circular economy within the next five years (Williams, 2012).

Political factors such as regulations encouraging manufacturers and suppliers to design for CE, regulations for product and material transparency similar to the digital battery passport, and regulations increasing the responsibility of manufacturers for their product circularity would improve CE initiatives. In contrast, reduced regulations and financial motivations such as fundings for any environmental improvement of products and infrastructure may hinder the CE approach. In addition, varying regulations from state to state as well as trade barriers and tariffs make global approaches difficult. Since the automotive industry and the vehicle lifecycle consists of different global spread stations, those risks can negatively impact CE.

Supporting economic factors are the business potentials based on increasing metal prices, a growing demand for recycled materials requiring CE, and the potential for new value streams based on those factors. At the same time, CE improvements and especially processes to gather better sorted materials require high investments. Based on the supply of ELVs which might fluctuate, the utilization of this high investment is uncertain. Also, the scrap material prices can fluctuate based on the uncertain and fluctuating market volume, which is a risk for the return on investment (ROI).

Customers and especially younger generations value and support CE approaches but might not know about or even want remanufactured parts in their vehicles. In addition, CE and recycling might be differently appreciated globally, which hinders global approaches for product circularity. Another social aspect is the demographics and lack of skilled workers which increases labor costs and requires the development of automated solutions when introducing disassembly processes.

Technology can be supported by innovation and digital advancements. Better traceability for parts and materials during the entire product lifecycle can improve the efficiency of CE processes. A risk for CE would be the approach of more integrated components with multi-material design which would challenge disassembly and recycling capabilities. One of the aspects for CE in automotive is the collaboration between different stakeholders. Companies might be challenged with a share of the economic benefits when collaborating.

Environmental factors include the emission reduction potential. The recycling processes as well as a new designed and introduced disassembly process itself creates emissions based on energy assumption and even pollution that needs to be considered in the overall emissions evaluation.

Some of the legal considerations are based on political factors. Regulations and funding programs can guide the industry in CE development. However, regulations can also be too complex and overregulate aspects of vehicle development and manufacturing as well as recycling, so that companies refrain from the CE approach. In addition, regulations or funding programs might be delayed or stopped based on the political situation in different regions. The risk of trade barriers is mentioned earlier with political factors.

Table 5 PESTEL industry analysis according to CE approaches in automotive industry based on (Kaufmann, 2025)

Factor	Opportunities	Challenges/ Risks
Political	Encouragement for sustainable vehicle design; extended producer responsibility; product passports increase transparency	Import and export tariffs and trade barriers; rollback BEV subsidies and infrastructure; rollback clean energy support; fragmented global regulations; political instability
Economic	Metal price increase attracts recycling; new value streams; growing demand for recycled components	High investment; fluctuating metal prices and uncertain ROI; supply chain disruption impacts circular flows
Social	Growing customer awareness; support of longer vehicle lifespans; value of circularity	Lack of knowledge about CE product options; resistance to using remanufactured parts; cultural differences in recycling behavior across regions; lack of skilled workers and demography
Technological	Innovation and technology improvement push; digital traceability of parts and products; design for disassembly; blockchain; improvement of shredding and sorting technologies	Fast technical improvements challenge recycling capabilities; complex design complicates recycling; need for cross-industry collaboration
Environmental	CE reduces resource extraction; reduced mining impacts	Pollution and energy consumption of recycling processes; risk of greenwashing
Legal	Emission standards; research & development funding for circular economy projects; legal mandates for recyclability	Complex certification processes; delay of emission and recycling regulations, uncertainty about liability of reused components; export restrictions

5.2.2 Porter's 5-Forces analysis

In addition to the macro-environment analysis the Porter's 5-Forces industry analysis is performed and the results are shown in Table 6.

Table 6 5-Forces analysis of car body disassembling based on (Porter, 1980)

Force	Threat	Details
Potential entrants	Low	High investment required; economies of scale: high volume production more efficient
Potential substitutes	High	Improvement of post-shredding sorting processes
Power of suppliers	High	No supply chain of ELVs established, fluctuating regional ELV volume
Power of buyers	Moderate	Sorted materials improve recycling efficiency; current processes do not reflect this potential
Competitive rivalry	Moderate	Single approaches in labs or pilot factories at automotive manufacturers; threat might increase with industrialized solutions

The disassembly requires high investments and high labor costs for manual operations or investment in automation processes. As a result, the risk for potential entrants is low.

One of the main economic questions is about the differences between the introduction of a new process prior to or advancement of existing sorting technologies after the shredding process. If the post-shredding sorting processes can improve the purity of the different materials and alloys, a disassembling process might not be necessary and therefore substituted.

Another concern for a disassembly process is the supply of raw material, in this case ELVs. A supply chain needs to be established, competing with ELV exports and current recycling processes. In addition, the volume of ELV potential can hardly be predicted on a regional base and might fluctuate. If soon the vehicle design will support longer use cycles with repair options, the number of vehicles for disassembly will decrease as well. In summary, the supply of ELVs is at high risk.

In contrast, the current recycling processes take the material contamination into account. To supply sorted materials of improved purity opens new opportunities for the recycling processes. The threat is moderate as the processes and business opportunities need to be established.

The disassembly process is not yet established in industry but tested in research laboratories as well as automotive manufacturers and partners shown in chapter 2.3. As a result, the current competition threat is low to moderate but might increase soon.

The analysis shows the potential threats and indicates several risks that should be considered.

5.2.3 Multiple future forecasting scenario analyses

Figure 8 shows the key elements of the macro-environmental PESTEL analysis performed in chapter 5.2.1. One of the important factors for the multiple future forecasting analysis is the scope of the study. Based on the research question the focus is on the efficiency of ELV material purity prior recycling. The future should have a range of about five years. While regulations and tariffs can have a high impact on the circular approach in automotive industry, they are almost predictable. Even if regulations are slowed down with currently experienced political and legal rollbacks, the long-term direction for an improvement of circular economy is globally solid. Technical improvements such as automation and part traceability can support the disassembling approach with medium impact and are also predictable considering the current evolution of automation in different areas. Collaboration approaches support the circularity with little impact on the technology approaches of pre-shredding disassembly or post shredding sorting. The identified key drivers of change are in the right upper corner of the diagram indicating high uncertainty and impact. The technological improvement of the post-shredding sorting process can have a high impact on the decision of disassembling prior shredding or not. The economic factor of profitability is associated with a higher degree of uncertainty and potential impact. In this case profitability combines the investment for a disassembling process and the projected return including the fluctuation of the material price. The design for disassembly will be mentioned as a third factor in this study. Improvements in this area can have a moderate too high influence on the chosen processes. However, if the design is changed today by car manufacturers and suppliers, ELVs in fifteen years or more would be affected, which is not in the scope of the five-year forecast.

As a result of the impact and uncertainty analysis the sorting technology and profitability are chosen as the key drivers for change to create four future scenarios.

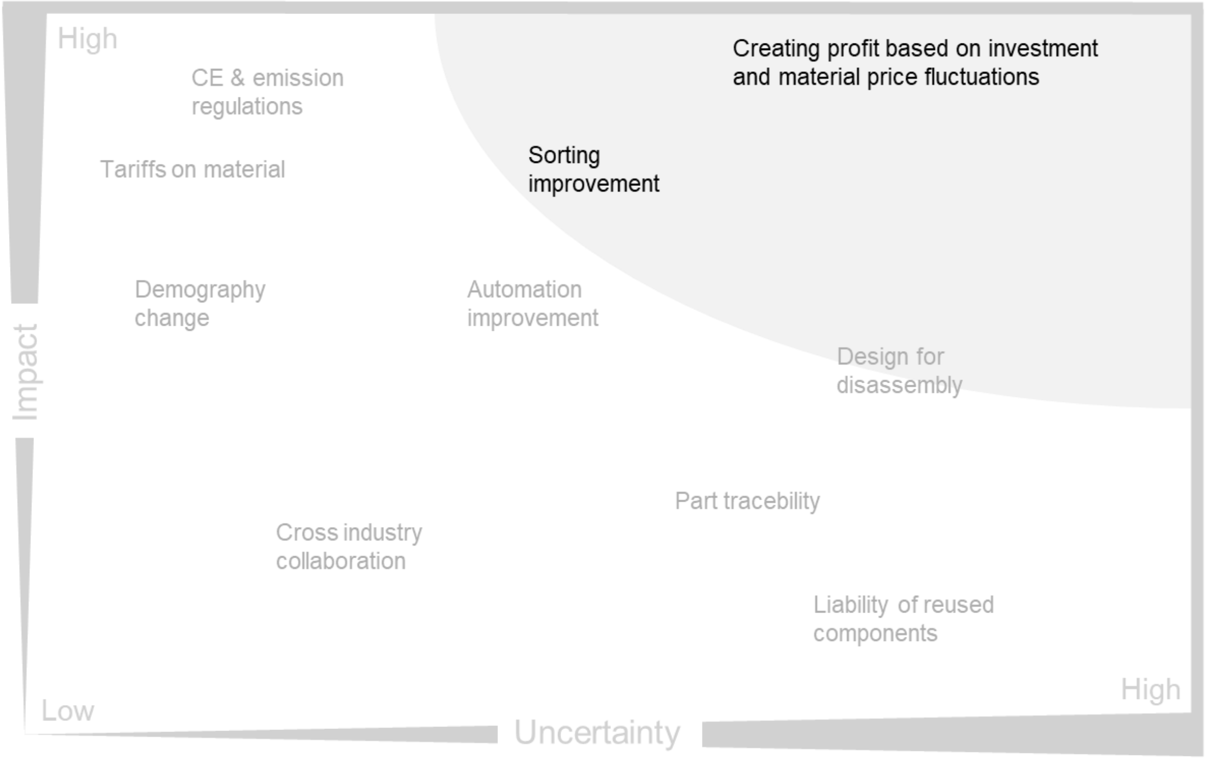


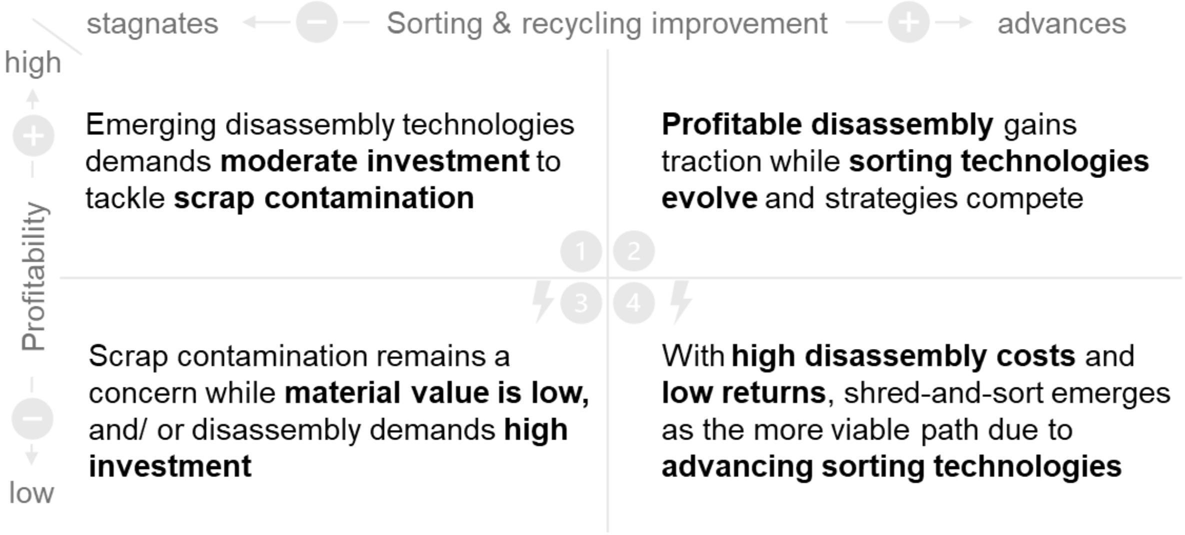
Figure 8 Impact and uncertainty diagram for PESTEL analysis of CE in automotive industry (created by the author)

The first scenario shown in Figure 9 describes a future with sorting and recycling technology existing today. It is very hard and expensive to improve the current state of sorting, and the recycling industry focusses on the delivery of the metals accepting current contaminations and therefore lower scrap metal purity. At the same time the investment for disassembly process lines is moderate and the delivery of better sorted material is beneficial considering the return on investment. In this scenario it is beneficial to invest in disassembling technology.

The second scenario considers advancements in sorting technologies. The material prices and therefore the profitability are high while the investment in disassembly technologies is reasonable. In this scenario both approaches, the disassembly and post-shredding sorting compete. The investment in disassembly processes needs to be highly efficient compared to the competing technologies.

In the third scenario the sorted scrap material price is low while the investment is still high for disassembling technologies. The sorting methods are sufficient for the recycling businesses and further development in sorting materials shows technical roadblocks or are too expensive. In this scenario the introduction of disassembly processes is at a high risk.

Scenario four has the same market conditions with low material prices and high investments, while the sorting technologies rapidly evolved into more efficient. This scenario is a very high risk for the investment into disassembling technologies.



Emerging disassembly technologies demands **moderate investment** to tackle **scrap contamination**

Profitable disassembly gains traction while **sorting technologies evolve** and strategies compete

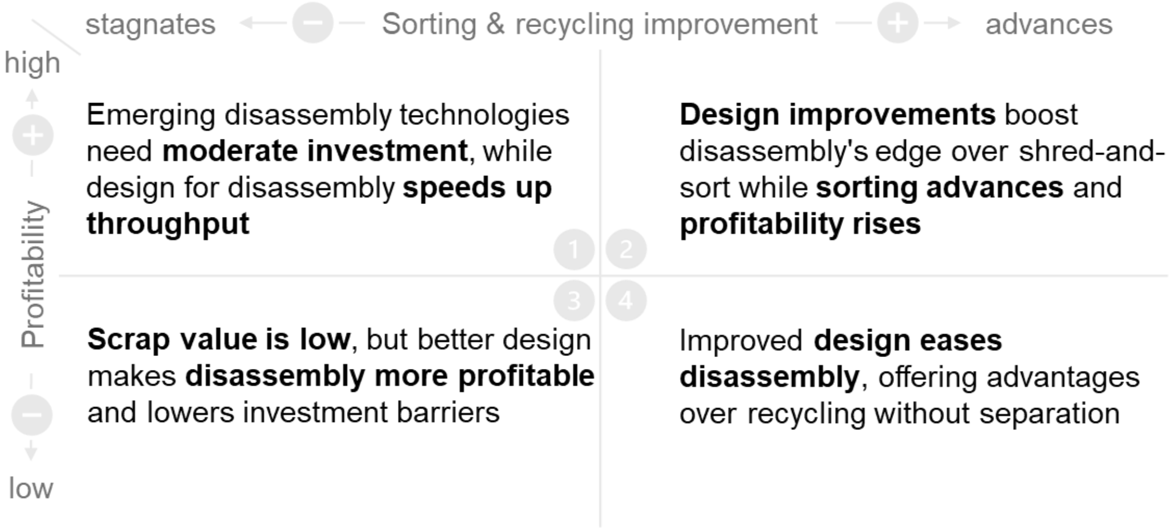
Scrap contamination remains a concern while **material value is low,** and/ or disassembly demands **high investment**

With **high disassembly costs** and **low returns**, shred-and-sort emerges as the more viable path due to **advancing sorting technologies**

Figure 9 Future scenarios based on the identified key drivers for change (5 years; created by the author)

In this multiple future forecasting with a five-year timeframe two out of the four scenarios are at high risk for a disassembling approach based on the key drivers of the investment, material prices and emerging competing processes.

Considering a future in fifteen or more years, when the first ELVs with design elements beneficial for disassembling processes start to enter the post operating phases, the scenarios would slightly change. The impact of a design for disassembly on the chosen scenarios should be also considered in this study.



Emerging disassembly technologies need **moderate investment**, while design for disassembly **speeds up throughput**

Design improvements boost disassembly's edge over shred-and-sort while **sorting advances** and **profitability rises**

Scrap value is low, but better design makes **disassembly more profitable** and lowers investment barriers

Improved **design eases disassembly**, offering advantages over recycling without separation

Figure 10 Future scenarios with improved design for disassembly (15+ years; created by the author)

In Figure 10 the matrix is shown with the same key drivers assuming similar uncertainty for material prices and technological development. The improvements in design according to the disassembly process boost all four scenarios for the benefit of the disassembling approach. The disassembling process can be less complex and therefore less cost intense compared to the scenarios based on current vehicle design. As a result, the design for disassembly pushed by regulations adds another important dimension to the scenario analysis and the research question, just in another timespan.

5.3 Business evaluation

The thesis also aims to outline an economic review of the disassembly process. According to the insights from the interviews, the identified drivers and impact from the scenario analysis, in this business evaluation variables for different uncertainties are considered.

The baseline of the analysis are assumptions based on the current material process, a disassembly process layout assumption as well as assumptions about the material mixes. The assumptions are based on available data analyzed and will be explained in the following sub chapters.

5.3.1 Input: ELV vehicle shell

The ELV vehicle shell needs to be ordered and transported to the disassembly line. To avoid huge logistic complexity, it is beneficial to limit the ELV sourcing area based on the disassembly location. Partnerships or business agreements with local authorized treatment facilities are beneficial for sourcing ELVs. In addition, individual or company vehicle operators can be approached with ELV collection programs similar to the approach from Renault (RenaultGroup, 2025).

Vehicles in the EU need to be returned to the ATF free of charge for the operator if the car is still complete (European Parliament, 2000). The disassembly process chain starts with the vehicle shell delivered from the ATF. In the usual ATF portion of the recycling process shown in Figure 5 includes the compressing of the car body for an efficient transport to the recycling facility. In case of disassembly the intact vehicle shell needs to be transported to the disassembling facility, logistic costs need to be considered. In addition, the ATF might sell the vehicle shell at a value recycling companies pay for the incoming mixed, contaminated and compressed material. Based on the availability of scrapped material and the actual price indication, the value of the input material might vary, driving the profitability as shown in the scenario analysis chapter 5.2.3.

5.3.2 Market: material price

The material of a vehicle and its components is the main driver for the carbon footprint. Therefore, it is one of the key tasks to close the material cycle by recovering material from the ELV. The automotive industry shows some examples whereas vehicle manufacturers together with recycling companies introduce development programs on material recycling. Chapter 2.3 highlights some good practices in this area.

Based on the material prices of several public sources the following paragraph shows the potential value of steel and aluminum in a new and end-of-life vehicle (FocusEconomics, 2025), (DailyMetalProces, 2025), (Bloomberg, 2025), (TradingEconomics, 2025), (WKO, 2025), (StahlpreiseEU, 2025). The different sources lead to similar prices which are presented in Figure 11 and the baseline for calculations in this thesis. When it comes to forecasting and business considerations, especially the scrap material prices need to be handled with care. Many geopolitical and -economic factors influence the prices.

In 2022 the average aluminum content per vehicle was about 205 kg with the largest portion of 123 kg from the aluminum casting type assembled in body in white e.g. shock towers, front and rear modules, and chassis e.g. in cradle nodes. The other aluminum types such as aluminum sheet, extrusions and forgings add up to 82 kg per vehicle on average. In the near future an increase to 237 kg per vehicle in 2026 and 256 kg per vehicle in 2030 is forecasted by European Aluminum (LLC, 2023). Assuming an aluminum price of EUR 2538 per ton in the year 2022, shown in Figure 11, and the 205 kg aluminum content per car, the material value for aluminum is about EUR 520.29 per vehicle.

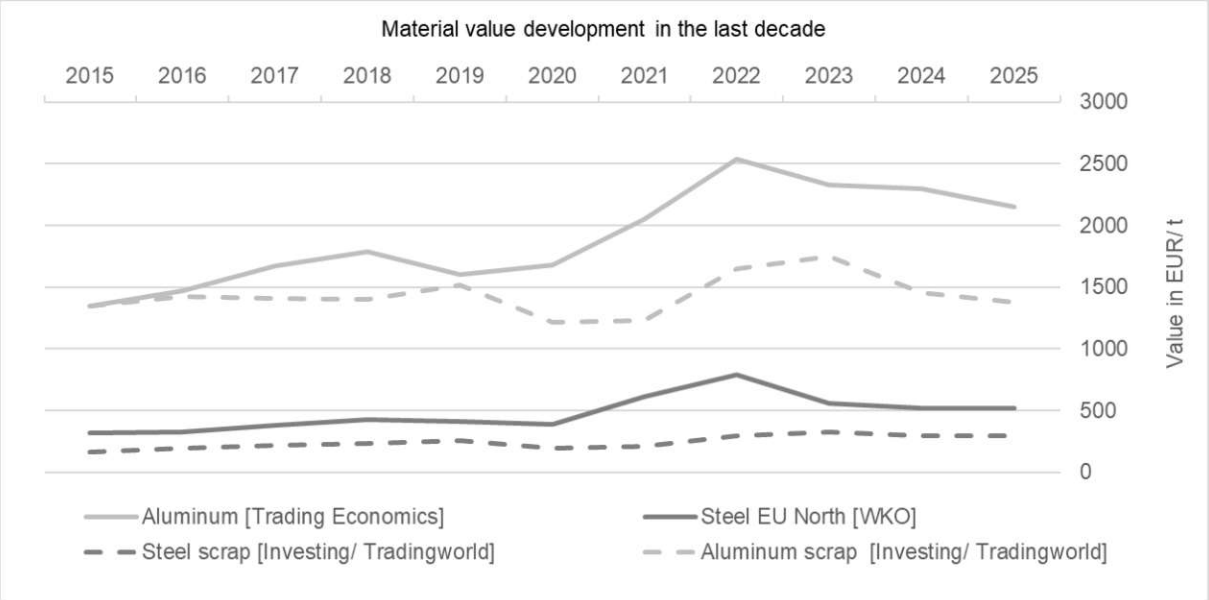


Figure 11 Material prices for aluminum, steel and metal scrap based on different sources (created by the author)

The steel content in a vehicle is at a minimum of about 800 kg. In contrast to aluminum scrapped steel requires additional processes for copper removal to become high-quality recycled steel, which is needed for the automotive industry. The copper contamination of about 0.2 % – 0.25 % in scrapped steel is caused by the high amount of copper cables for sensors and electric components in the vehicle. The contamination can cause defects during the product manufacturing processes. Automotive steel usually contains about 0.06 % copper content. Besides CO_{2eq} emissions the extraction and processing of high purity steel causes emissions of nitrogen oxides and sulfur dioxides and therefore has a significant environmental impact (Soo et al., 2016) in addition to the economic effort. For that reason, there is a gap between average steel scrap and average steel prices. Assuming a steel price of EUR 788.4 per ton in 2022 as shown in Figure 11, the calculated material value for steel is about EUR 630.72 per vehicle. Based on this calculated aluminum and steel content a new vehicle shows a value of EUR 1,151.01 considering the original material grade and value. In a comparison Table 7 lists the values for the scrapped material from an ELV, which is shredded and sorted. The aluminum grades would be mixed as well as the steel grades including the explained copper contamination.

There is an economic gap between the scrap material price and the new raw material price which results in a material value bisection as shown in Table 7. This of course is one snapshot of an analysis for metal shares from 2022 (LLC, 2023) and metal prices from 2022.

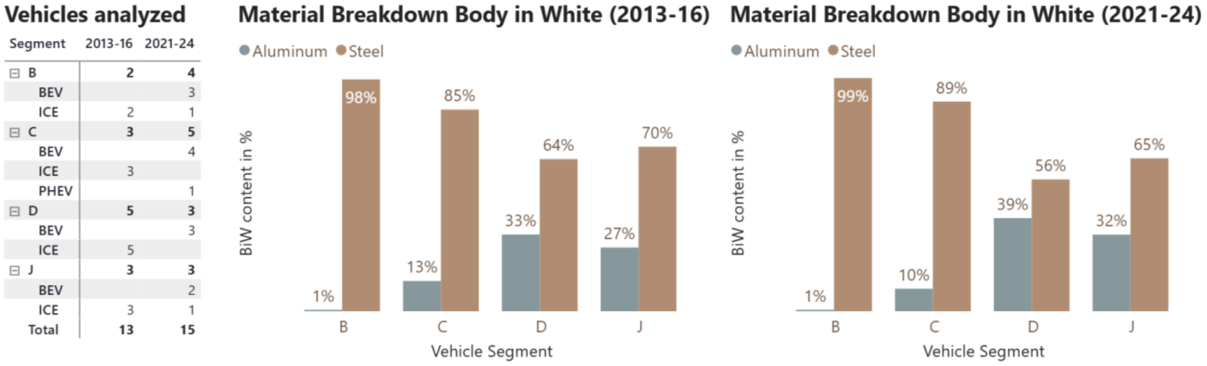
Table 7 Potential value based on material content and prices for a new and end-of-life vehicle (created by the author)

Case study 2022	Material value of new vehicle	Material value of end-of-life vehicle
Aluminum	EUR 520.29	EUR 337.23
Steel	EUR 630.72	EUR 232.80
Total Value	**EUR 1,151.01**	**EUR 570.02**

However, in interviews with material experts, the material prices considered for the outcome of the disassembly process should be the metal scrap prices, and not raw material prices based on better purity of the scrap. Based on this interview the purity of the scrapped material prepared for recycling has no significant influence on the material price. The availability of scrapped material will be the more significant driver for the material value of an ELV.

5.3.3 Output: sorted materials with high purity

First, the output depends on the incoming material mix from the ELVs. Based on the brand, segment and model the share of materials changes. For this study a data analysis of 28 vehicles with the focus on the material content share is performed based on data from the Global Car Body Benchmarking Conference in the years 2013 – 2024 (EuroCarBody, 2013-2024). The benchmark data summary for each vehicle is analyzed for the aluminum and steel content and segments are summarized based on two different model year time frames. Figure 12 shows the material breakdown per segment of the car design introduced in 2013-2016 and current car design launched in 2021-2024. For each segment and model year a range of 2-5 cars were analyzed. In current model years, the engine type is predominantly BEV while ten years ago the representative vehicles run with ICE. The material breakdown shows similar metal type shares between the model years with a slight increase of the aluminum content in the luxury (D) and SUV (J) car segments.



Vehicles analyzed

Segment	2013-16	2021-24
⊟ **B**	**2**	**4**
BEV		3
ICE	2	1
⊟ **C**	**3**	**5**
BEV		4
ICE	3	
PHEV		1
⊟ **D**	**5**	**3**
BEV		3
ICE	5	
⊟ **J**	**3**	**3**
BEV		2
ICE	3	1
Total	**13**	**15**

Figure 12 Material breakdown of representative vehicles per segment 2013-16, 2021–24; based on data from (EuroCarBody, 2013-2024)

The main differences in the material share occur between the segments as Figure 12 demonstrates. While the B-segment vehicles are almost purely designed in steel, C-segment cars already consist of about 10% of aluminum and the D-segment vehicles consist of about 30-40% of aluminum.

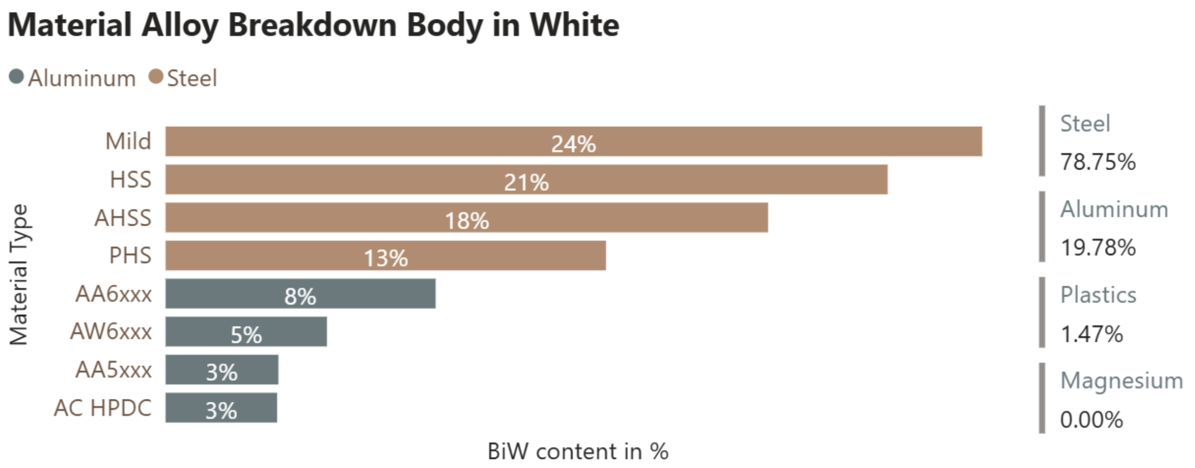


Figure 13 Average material alloy breakdown for all analyzed vehicles, segments and years; based on data from (EuroCarBody, 2013-2024)

The breakdown of the different alloys in Figure 13 shows that the 6000-aluminum alloy extruded (AW6xxx) or as body panel stamping (AA6xxx) dominates the aluminum share, followed by aluminum 5xxx-series and high pressure die casting alloys. The current approach and development in aluminum high pressure die casting might boost this number in the next design generations. The different aluminum alloys should be separated and sorted; the steel grades can be kept assembled in modules.

Since a car body in the B-segment after the process of interior disassembling almost purely consists of steel, the car body disassembly is not necessary for a pure material recycling process and could be shredded like the current processes without car body disassembling. However, in the suggested process chain in Figure 16 the separation into modules is considered for easier handling and logistics.

C-, D- and J- segments consisting of mixed aluminum and steel alloys are required to be disassembled for better material purity prior shredding.

Besides the analyzed segments A/B for small subcompact cars, C for lower medium compact cars, D for upper medium mid-size cars and J for sport utility vehicles (SUV) in Figure 12 the segments E/F for luxury and executive cars and M for multi-purpose vehicles (MPV) exist. For those segments the same material share from the D segment is assumed for subsequent calculations.

For the business evaluation an assumption for the return of scrapped material needs to be made. Considering the current metal prices in Figure 11 the aluminum in ELV has a value of about 1,400 EUR/ t and the steel of about 300 EUR/ t.

Table 8 Cars in EU 2015/ 2023 and brief material mix 2013-16/ 2021-24; based on data from (EuroCarBody, 2013-2024)

Segment	**EU share 2015**	**Al | Steel share 2013-16**	**EU share 2023**	**Al | Steel share 2021-24**
A/B – Small	31%	0% | 100%	21%	0% | 100%
C – Compact	23%	15% | 90%	15%	10% | 90%
D – Midsize	9%	35% | 65%	6%	40% | 60%
E/F – Luxury	3%	35% | 65%	2%	40% | 60%
M – MPV/ Van	12%	35% | 65%	4%	40% | 60%
J – SUV	22%	30% | 70%	51%	30% | 70%

SUVs in Europe have increased their share of about 22% in 2015 to 51% in 2023 while the share of C- and D-segments decreased by 10% in the same time span. Table 8 summarizes the car share by segment based on the European Automobile Manufacturers' Association (ACEA, 2024) and the material content based on the analysis in Figure 12 for the two different timeframes around 2015 and the recent years. The vehicles introduced around 2015 with an operational lifetime of 15 years would 2030 ELVs, while vehicles produced in the last few years would hit the end of their life earliest in the 2040th. In addition to the uncertainty of the vehicle lifetime, the availability of ELVs in the different segments is uncertain due to ELV exports outside the EU mentioned in chapter 1. However, to create a business evaluation, in this study the segment shares and material mix displayed in Table 8 are considered. Equation 1 shows the calculation for a potential outcome material price per ton of the input ELV.

Equation 1 Potential outcome without any loss considerations (created by the author)

$$\begin{aligned}
&\big(Share_{A/B} \times Share_{Al,A/B} + Share_{C} \times Share_{Al,C} + Share_{D} \times Share_{Al,D} \\
&\quad + Share_{E/F} \times Share_{Al,E/F} + Share_{MPV} \times Share_{Al,MPV} \\
&\quad + Share_{SUV} \times Share_{Al,SUV}\big) \times Price_{\,Al} \frac{€}{t} \\
&\quad + \big(Share_{A/B} \times Share_{Steel,A/B} + Share_{C} \times Share_{Steel,C} \\
&\quad + Share_{D} \times Share_{Steel,D} + Share_{E/F} \times Share_{Steel,E/F} \\
&\quad + Share_{MPV} \times Share_{Steel,MPV} + Share_{SUV} \times Share_{Steel,SUV}\big) \times Price_{\,Steel} \frac{€}{t}
\end{aligned}$$

Based on the assumed segment and material shares and material prices, the disassembly material outcome without any considered losses would be about EUR 506 per ton ELV in 2030 and about EUR 535 per ton ELV in 2040 following the calculation in Equation 1 with the subtotals listed in Table 9.

Table 9 Potential ELV material revenue (created by the author)

Year ELV	Aluminum	Steel	Total	Risks
2030	258.30 €/t	248.10 €/t	506.40 €/t	Uncertain prices, material losses during the process operation
2040	302.40 €/t	232.20 €/t	534.60 €/t	

5.3.4 Process: disassembly

While the assembly process chain starts with the single material part and follows the subassemblies consisting of multiple joined single parts to the final assemblies of a body in white or chassis module, the disassembly process chain begins with the module and follows the same opposite route to the single material part.

In an ideal environment, assembly and disassembly processes are based on the same method or technology. As a simple but popular example from the toy industry, the interlocking plastic bricks can be assembled to create a specific product. In the same way but opposite direction, the product can be disassembled to generate a stockpile of single bricks again.

The scenario and the logic of a reverse assembly to get to the single part and therefore the material in pure quality involves some challenges and considerations. First, it might not be necessary to separate all parts. The steel manufacturers can handle different grades of steel when remelting the material, just the copper contamination from entirely shredded ELVs is a problem as described in chapter 2.5. In contrast, the aluminum different alloys should be separated from each other to maintain the base alloy for the recycled aluminum. The main need for separation would be material mixes of steel and aluminum, also due to joining elements such as steel Self-Pierce Rivets (SPR) that are joining aluminum sheets. As the architecture of each car model can be unique, there won't be a standardized separation or disassembly method fitting all products to maximize material recovery. Second, the overall assembly process of a vehicle contains the car body assembly of metal sheets as well as the final assembly including interior installation, glass and seals, powertrain installation and chassis components. Based on Figure 5 the hazardous materials and parts are removed and valuable parts of the ELV as well as glass are recovered for a secondary market or recycling, so the vehicle shell containing interior, and the car body would be the starting point for disassembly. The process step of disassembling interior parts such as dashboards, seats, carpets and wiring harnesses needs to be considered in this study as well, even when the thesis focusses on car body disassembly. To distinguish between both processes the study terminology is interior and body disassembly as shown in Figure 7.

5.3.5 Interior disassembly

Figure 5 and chapter 2.3 describe the process steps prior compacting and shredding the vehicle shell. Tires, hazardous materials, parts that can be reused such as engines and transmission systems, electronics and some glasses are removed. The seats and interior as well as cables for electronics are remaining in the vehicle and part of the compacted and subsequently shredded mixed materials.

The predominant joints for the final assembly between the interior components and the car body are screws and clips. The reverse process would be unscrewing or pulling and ripping the interior parts and wiring harnesses. With state-of-the-art vision guided robot systems, mounting points as well as the specific joining element can be identified to automatically choose the right tool and unmount the part. That would be required for dismantling the bigger and heavier parts such as seats. In addition, assembly instructions or a digital twin of the ELV from the car manufacturers can help to identify the mounting points and decide quicker on the required dismantling steps and technologies. In contrast and potentially faster for lightweight interior parts, grippers could strip out the elements roughly and remove them. Especially with mounting systems designed for single use such as clips, rough methods need to be considered for dismantling. Removable joining methods such as screwing and bolting with accessibility for the reversed process steps according to the interior assembly can optimize the ELV dismantling.

The predominant method for assembling interior components is adhesive bonding, which creates a problem for disassembling approaches. Especially different plastics glued together can barely be separated and therefore are lost for any recycling process. In contrast to the car body disassembly described in chapter 5.3.6 interior materials can easily be destroyed with efforts to separate the materials. Table 10 highlights the main joining methods, the applications and potential disjoining methods.

Table 10 Disjoining methods for interior disassembling (created by the author)

Joining Method	Applications	Disjoining Method
Mechanical Fastening	Seat, dashboard, trim panel	Unscrewing, drilling
Adhesive Bonding	Trim, fabrics, mixed materials	Chemical/ thermal debonding
Thermal Joining	Plastic ducts, panels, housings	Cutting, localized heating
Snap-Fits & Interlocks	Door panel, console, glove box	Un-snap, pry tools
Sewing/ Stitching	Upholstery, steering wheel, soft trims	Thread cutting, unpicking

The disassembly of interior design to separate and recover materials for recycling shows challenges and roadblocks that are not easy to overcome. A disassembly of the interior components from the car body just makes sense in combination with the mainly interior free car body to increase the potential of pure metals for the recycling process. In return, this process step needs to be considered for the entire process and business evaluation.

5.3.6 Car body disassembly

The car body assembly is designed to fulfil several functions and requirements. Figure 14 shows an example of an assembly process for a body-in-white module. The product shows parts of different material grades that are joined to subassemblies following the tree in the right direction. The numbers in front of a subassembly (1-4) represent different joining technologies. As an example, part D and E of different aluminum grades are joined with the technology 3 to create the subassembly (1), while subassembly (6) joined with technology 1 consists of part L, part M and subassembly (3), which is an assembly of parts I and J joined by technology 1. The entire car body assembly follows this part tree logic specified in the bill of materials.

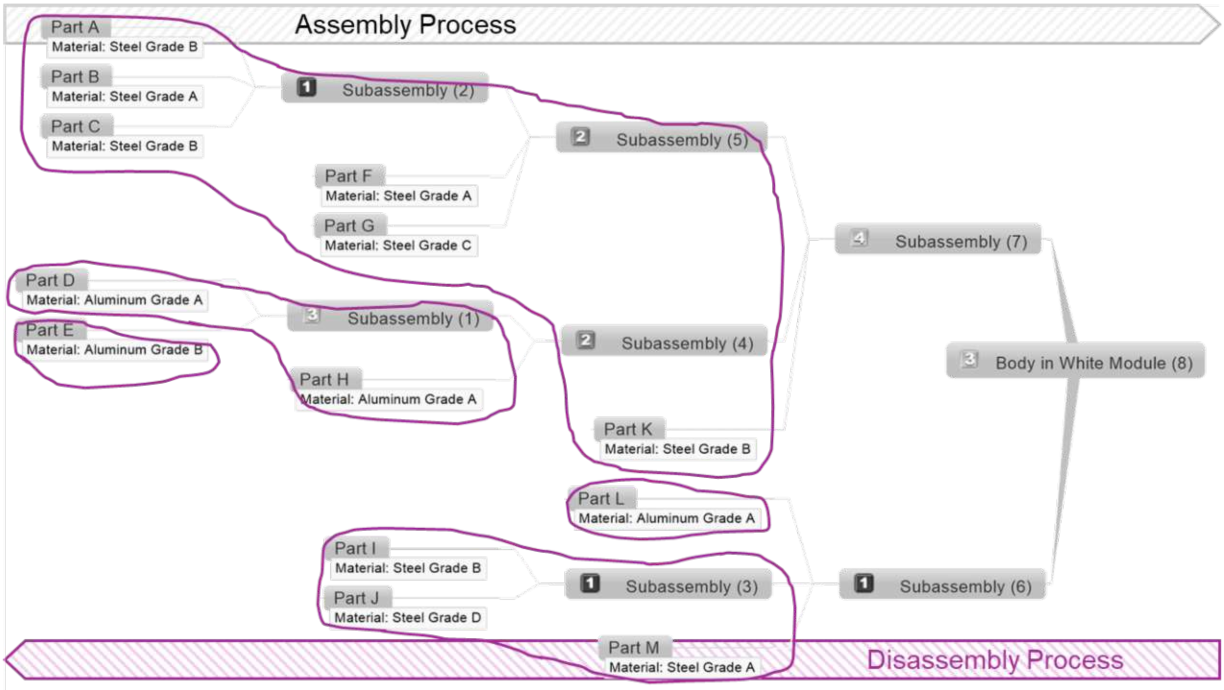


Figure 14 Example of a product tree following the assembling or disassembling direction (created by the author)

A body disassembly process follows the reverse direction but not necessarily all the process steps as described earlier in the chapter. To recover the materials for the recycling process as pure as possible, steel and aluminum, as well as the different aluminum grades need to be separated, steel grades can be kept joined. In Figure 14 the disassembly process for subassembly (6) following the tree to the left direction needs to reverse the joining method 1 to separate part L made of aluminum from the other parts made of steel. Subassembly (3) made of the steel parts I and J, and the part M as part of the subassembly (6) do not need to be disjoined as the steel can be recycled in different grades. In this example an assembly of 13 parts joined with four different technologies can be disassembled into four groups, represented by the purple frames in Figure 14, but also facing all the four joining methods for disjoining. In addition, the material handling process needs to be considered as it might be beneficial to separate subassemblies of large sizes into smaller components that can easier be handled.

There are a variety of passenger vehicles on the road in each region, country and city. Therefore, the starting product for a dissembling process chain would not be homogenous but variable in size, design, material, joints and part count. The disassembly process chain also requires flexibility to the incoming end-of-life product.

Flexible disassembling for generic products can be planned by models considering the incoming product, desired outcome that defines the dissembling processes and chain, as well as the state of the product such as recycling purity, waste and hazardous items (Ullerich & and Buscher, 2013).

Two main approaches can be chosen to disassemble components. The first and rough approach utilizes forced separation processes that are independent from the joints between the materials. For example, two metal sheets joined by Resistance Spot Welding (RSW) as shown in Figure 15 a) are laser cut on the flange above the spot welds. Therefore, one part of the material contains residues from the second material as the separation process design does not reflect the joining design as shown in Figure 15 b). The second approach utilizes disjoining methods on the joints, in the previous example the Resistance Spot Welds. The separation process could be a drilling of the spot welds. In this case both separate materials contain the original parent material without any residues of the other material as shown in Figure 15 c).

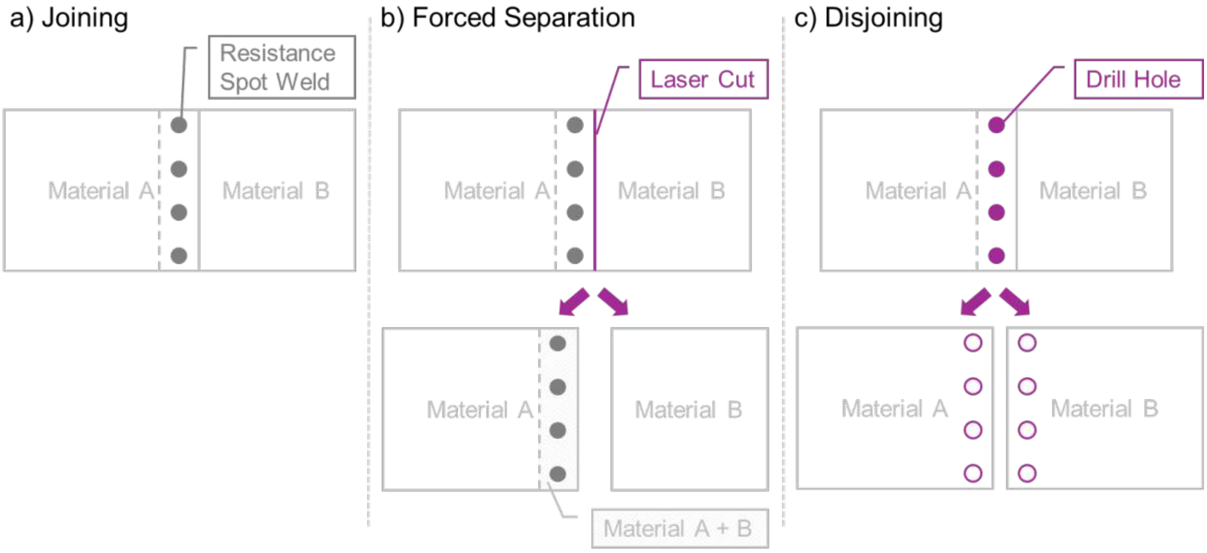


Figure 15 Example of the main separation methods (created by the author)

While the disjoining method provides better purity of the parent materials, the forced separation method can be simpler and faster. Besides the specified classification of joining methods, joining technologies can be divided into discrete joints providing strengths in individual, distinct joints, and continuous joints providing strength across the entire length of the joint area. The next paragraphs provide more details on each separation method classified for discrete and continuous joints.

Discrete joints such as Resistance Spot Welds (RSW), Self-Piercing Rivets (SPR) or Laser Beam Welding (LBW) stitches can be drilled to separate the parent material. Car body workshops are using today specific drill bits on pneumatic drilling machines to disassemble and replace damaged panels. For this manual operation an operator needs about three minutes per joint based on the experience of those workshops (Carter, 2025).

Some companies offer plasma machines to melt the discrete joint. The process is called precision gouging and requires some training and intuition of the operator. In return the process can be as fast as about ten seconds per joint (Hypertherm, 2025).

Laser cutting can be another disjoining method, which provides a precise cut around the discrete joint to separate the parent materials. This method would be just applicable in automation due to operator safety. Depending on the material thickness and shape of the discrete joint, laser cuts can be as fast as several seconds per joint.

Another automated method could be the milling of the joint. Like drilling the entire joint is removed by the milling tool to separate the parent materials. The process can take about one minute per joint.

Continuous joints such as Gas Metal Arc Welding (GMAW) or Laser Beam Welding (LBW) are difficult to separate as they are designed to fuse the metals along a certain length with similar material characteristics such as melting temperature compared to parent metals. In repair shops welds get separated by grinding as close as possible to the parent metal without major damaging of the surrounding parts. In addition, gouging processes can be used to melt the weld zone and blow out the molten material.

Brazing processes such as Laser Beam Brazing (LBB) are often used for visible joints that don’t require a high strength or joint performance. The brazing solder has a lower melting point of up to 950°C than the parent steel parts, which are melting at about 1600°C. This enables a disjoining with heat input of about 1200-1500°C without damaging the parent metals. The Fraunhofer IWU investigated into a defocused laser process to accomplish the disassembly. To provide a constant process, the temperature of the process is controlled by sensors. The molten brazing solder is blown out with process gas similar to gouging processes. The process is proven feasible and can be applied to a robot for flexibility (Paizs, 2025).

Another popular joining method in car body applications is adhesive bonding. Adhesives in body in white applications can provide strength, stiffness, compensation for tolerances or seal areas that require sealings. Based on the different functions there are a variety of different adhesive types available. As an example, epoxy adhesives provide high strength and are used for structural bonding, while polyurethane adhesives are flexible and used to join body panels to reinforcements. Adhesives can be disjoined by applying heat of about 200°C to soften the bond. Some types of adhesives can also be chemically dissolved. Both methods make a lot of effort and therefore alternative approaches to separate glued assemblies are in research.

The Fraunhofer IFAM developed a process for a controlled disjoining of adhesive bonding. A new polyamide adhesive is the key element of this investigation. The adhesive provides similar strengths compared to structural adhesives on car body materials. When applying a heat of 65°C and a small voltage of 48V at the same time, the adhesion drops significantly. As a result, an adhesive fracture occurs, and the adhesive can be peeled off the parent material without any remains. Additional studies focus on different adhesive materials similar to currently used types (Mayer, 2025). This investigation shows some potential solutions for disjoining methods of adhesive bonding.

Another challenge occurs according to car body structures. Multiple adhesive bonding flanges also come with discrete joints such as RSW and SPR. The applied adhesive cures with heat in the drying oven of the paint shop, so that the adhesive in the body shop is uncured and soft. To maintain the dimensions of the car body when transporting it through the assembly stations, an additional joining method is required. Another reason for hybrid joints of adhesive bonding and RSW or SPR is the excellent joint performance, combining stiffness by the adhesive and punctual strength by the discrete joint. The combined joints challenge the disassembly approach.

Based on the experience of engineers and operators in the repair business, the different disjoining methods can achieve speeds between 10 mm/ s and 50 mm/ s on an average gauge stack-up of about 3 mm. The different methods also vary in precision and heat input which may damage the parent material (AES, 2023), (ProCAM, 2025), (Raymond, 2025).

In Table 11 all the explained disassembling methods according to the assembling methods are listed, including some high-level characteristics such as precision, heat input and effort. The effort represents investment, e.g. a laser cell for laser cutting processes. The estimated time per disjoint is called out based on publicly available information from repair shop forums, engineers and company websites (Carter, 2025), (Hypertherm, 2025), (AES, 2023), (ProCAM, 2025), (Raymond, 2025).

Table 11 Joining methods and disjoining options (created by the author)

Joint	**Disjoining Method**	**Time per disjoint in s**	**Precision**	**Heat Impact**	**Effort/ Invest**
Discrete Welding:	Drilling	180 s	High	Low	Low
Resistance Spot Welding, Self-Pierce Riveting, Clinching, Laser Beam Welding stitches, Laser Screw Welding	Plasma Gouging	10 s	Medium	Medium	Low
	Laser Cutting	3 s	High	Low	High
	Milling	60 s	Medium	Low	Medium
	Grinding	60 s	Low	Low	Medium
Flow Drill Screwing	Unscrewing	5 s	High	N/A	Low
Continuous Welding:	Grinding	10 mm/ s	Medium	Low	Medium
Gas Metal Arc Welding, Laser Beam Welding, Hybrid Laser Arc Welding	Plasma Gouging	30 mm/ s	Medium	Medium	Medium
	Laser Cutting	40 mm/ s	High	Low	High
Laser Brazing	Laser Gauging	40mm/ s	High	Low	High
Adhesive Bonding	Melting	10mm/ s	High	Low	High

The Table 11 groups several discrete and continuous joining methods when the disjoining methods can be applied to all the grouped technologies. Also, the table just lists the disjoining of the actual joints and does not take the forced separation process as shown in Figure 15 into account. The disjoining methods described represent a clean separation of materials when required. Depending on the assembly the variety of disjoining methods can blow up the investment. The question arises whether a precise disjoining of the actual joint for all joints in the vehicle is necessary. A combination of rough breaking methods such as sawing or laser cutting and precise operations for a clean separation of materials could be an optimal way.

To summarize the subchapters of the disassembly Table 12 lists the key challenges and opportunities for the main categories such as the targeted material purity, required technology and process throughput considered as economic factor.

Table 12 Summary of disassembly challenges and opportunities (created by the author)

Category	Disassembly challenges	Disassembly opportunities
Material purity	Clean separation requires disjoining precision	Separation of mixed metals that are difficult to recycle
Technology	High investment, depending on effort for disassembling	Established processes, similar to assembly
Process throughput	Separation efficiency due to number of joints and resulting disjoining time	Combination of different disjoining methods to separate large modules fast and small components precise

5.3.7 Investment: disassembly line

The previous chapters describe the different technologies for the car body disassembling process. As a result of the interviews and analysis, the best approach aims to separate steel and aluminum but not different steel alloys. Figure 16 shows the brief process chain for both disassembly processes. The interface for the input is the vehicle shell from the ATF. The output is sorted material fragments ready to be shipped to recycling facilities.

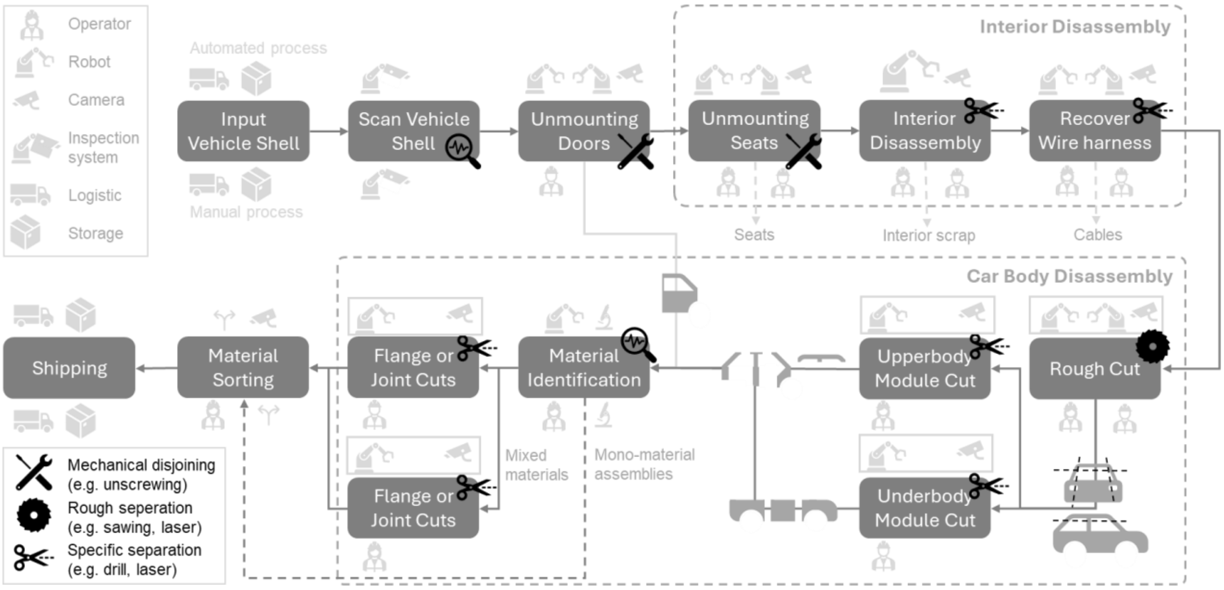


Figure 16 Proposed disassembly process chain (created by the author)

A first step can be a full scan of the vehicle shell with laser triangulation scanners or cameras to generate a digital model and cutting strategy according to the identified dimensions of the car body. In future stages the model and make could be identified, and based on a database with different disassembling strategies, an algorithm can decide about the necessary process steps, parameters and details. In the next step doors should be dismounted, mainly by unscrewing. This can be a manual step potentially with instructions based on the scan from the earlier step, or an automated step performed by a camera robot equipped with multiple tools to unscrew. If unscrewing is not possible based on model or condition, the hinge can be mechanically cut. The interior disassembly removing seats, dashboard, textiles would be the next steps followed by stripping out the wire harness. A quantitative impact study suggests that a removal of about 50% of the entire cable system would be sufficient to lower the overall copper content of the steel to less than 0.1% which is required to recycle high quality steels (Jürgen Sutter, 2025). The more copper gets recovered from the shell, the higher the quality of the material is. After the interior disassembly the car body can be taken apart. The suggested strategy would be a process chain of rough cuts to a module level. The first rough cut separates the roof and side frame from the underbody with mechanical or laser cuts almost at the bottom of A-, B- and C-Pillar. The upper body then gets cut into modules such as A-, B- and C-Pillar and the roof itself for better handling. The underbody gets cut into three modules such as the front-, mid-, and rear-module. The smaller modules get individually checked for the materials aluminum and steel e.g. by magnets, ultrasonic or eddy current testing, or by X-ray fluorescence analyzers (XRF) that are also available as handhelds (Bruker, 2025). If a material mix is identified, it needs to be decided how the module is taken apart. This can be again a manual step done by operators removing joining elements, spot welds or cutting off the entire flange, or by camera guided robots with cutting or even laser cutting equipment. For all disassembly steps some flexible fixture is required. In addition, internal logistics need to be set up with transportation between the different process steps. At the end of the process chain, the material gets sorted into the different aluminum alloys and steel and shipped to the recycling facility. Table 13 shows the process steps and the required equipment based on the throughput.

5.3.8 Throughput: disassembly scale

The authorized treatment facilities can have a throughput between 20 for smaller facilities and 300 vehicles per day for high throughput facilities such as European Metal Recycling Ltd. (Healey, 2023). The European Recycling Industries' Confederation outlines in their ELV regulation recommendations to support more efficient and high throughput ATFs (EuRIC, 2024). This study assumes a throughput of 60 vehicles per day, which results in a cycle time of 8 min per vehicle assuming eight hours shift operation with one shift per day. Based on the 3 million recycled vehicles per year in the European Union mentioned in chapter 1 and a total volume of 13,800 disassembled ELVs per year producing on 230 days, the market share would be about 0.5%. This can and needs to be scaled up to increase efficiency, but as those disassembly lines are not state of the art, there is limited information available for more precise assumptions.

The cycle time for mechanical cuts by grinding is about 10 mm/ s, so that 4.8 m is the maximum cut that can be achieved in the given 8 min cycle time. A laser cutting cell can theoretically achieve up to 19.2 m with 40 mm/ s process time. The process time highly depends on the material stack up. Rough cuts should be considered slower than cuts on thin flanges.

According to the cycle and cutting process time, the required equipment or operators per process step are roughly defined in Table 13. The manual disassembly requires 16 operators; a semi-automated scenario requires 10 operators and 2 robots while the fully automated option requires 15 robots. In addition, the equipment for tools, guidance, transportation and infrastructure and safety is required. Considering an investment of EUR 300,000 for each manual and 500,000 for each automated process including the standard equipment, and extra costs for the special equipment e.g. EUR 1,000,000 for the scanning equipment, another EUR 500,000 for the heavy-duty robot including foundation and special tools, and 3,500,000 for the internal logistics, fixtures, warehouse and overall infrastructure, the total investment assumptions are about EUR 7.8 Mio for the manual, EUR 8.0 Mio for the semi-automated, and EUR 10 Mio for the automated disassembly line.

Table 13 Brief requirements for each process step depending on degree of automation, cycle time of eight minutes assumed (created by the author)

Process step	Manual	Semi-Automated	Automated
Input vehicle shell	• Logistic, storage	• Logistic, storage	• Logistic, storage
Scan vehicle shell (Scanning Process)	• 1 Operator • Scan equipment	• 1 Robot • Scan equipment	• 1 Robot • Scan equipment
Unmounting doors (Separation Process)	• 1 Operator (2 min/ door)	• 1 Operator (2 min/ door)	• 2 Robots, 1 per side, camera
Unmounting seats (Separation Process)	• 2 Operators (4 min/ seat)	• 2 Operators (4 min/ seat)	• 2 Robots, 1 per side, camera
Interior disassembly (Separation Process)	• 2 Operators	• 2 Operators	• 1 Heavy duty robot
Recover wire harness (Separation Process)	• 2 Operators	• 2 Operators	• 2 Robots, camera
Rough cut (Separation Process)	• 2 Operators, 1 per side	• 2 Operators, 1 per side	• 2 Robots • Cutting cell
Module cut (Separation Process)	• 2 cells with 2 operators	• 2 cells with 2 operators	• 2 cutting cells with 2 robots
Material identification	• 1 Operator • Checking device	• 1 Robot • Checking device	• 1 Robot • Checking device
Flange or joint cuts (Separation Process)	• 2 cells with 2 operators	• 2 cells with 2 operators	• 2 cutting cells with 2 robots
Material sorting/ quality assurance	• 1 Operator	• 1 Operator	• Automatic transfer
Shipping	• Logistic, storage	• Logistic, storage	• Logistic, storage

5.3.9 Summary business evaluation

A lot of assumptions must be made, but the brief business evaluation shows the following results:

1. *Assumptions*

- Output: 13,800 disassembled ELVs with about 700 kg per vehicle shell = 9,660 t_{ELV}
- Efficiency: 80% efficiency or 20% material losses due to rest contamination and cutting scrap = 7,728 t_{ELV}
- Operational costs: EUR 80 per hour labor costs and EUR 20 additional operating costs for manual and EUR 50 for automated processes including energy, consumables, spare and wear parts and overhead lead to total costs per year according to the process layout in Table 13:
    - Manual production: EUR 2.94 Mio
    - Semi-automated production: EUR 2.02 Mio
    - Automated production: EUR 1.38 Mio

2. *Results*

- 2030 ELVs:
    - Revenue: EUR 3.91 Mio
    - Manual production: EUR 0.87 Mio profit; 9.0 years investment payback
    - Semi-automated production: EUR 1.79 Mio profit; 4.5 years payback
    - Automated production: EUR 2.40 Mio profit; 4.2 years payback
- Revenue 2040 ELVs: EUR 4.13 Mio
    - Manual production: EUR 1.09 Mio profit; 7.2 years investment payback
    - Semi-automated production: EUR 2.00 Mio profit; 4.0 years payback
    - Automated production: EUR 2.62 Mio profit; 3.8 years payback

Since the assumptions are brief the results should demonstrate the major influences on a potential business opportunity. The degree of automation has a huge impact on the operating costs and therefore the profitability of a disassembling line. Standardized processes can optimize the process chain and efficiency, increase the throughput and as a result the outcome generating more revenue. The third main driver in a business evaluation is the material price creating the revenue.

To verify the impact of each key factor of the assumptions a sensitivity study is performed. In different cases each key factor is changed by 25% compared to the baseline and the overall profit is calculated and presented in Figure 17. The entire calculations can be found in the appendix 8.2.

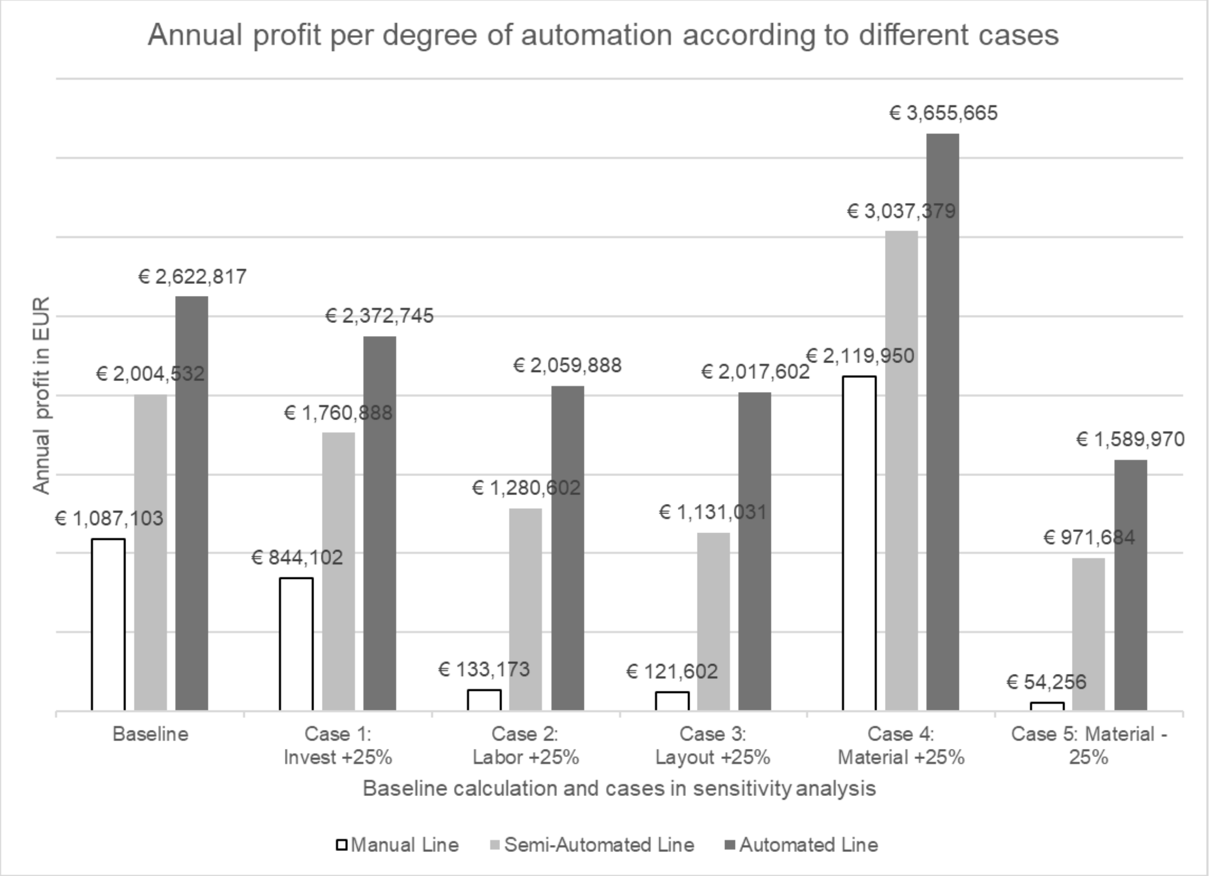


Figure 17 Sensitivity study for the automation level according to different cases (created by the author)

Case 1 considers higher investment costs by 25% of the baseline assumptions. The increased investment decreases the profit rates in a similar way for each degree of automation. The impact is not considered significant. In case 2 the labor and operational costs increase by 25% which influences not only the manual process chain but also the automation due to higher energy or consumable costs. In contrast, the impact is more significant for manual processes as the profit drops by 87% while the automated process chain loses 20% profitability. The third case considers more complex processes resulting in additional equipment, cells, robots and operators. This layout in terms of required personnel and robots increases by 25%, which shows similar effects as case 2. The profitability for a manual operation drops significantly by 90% while the profit of an automated line decreases by 23%. The last two cases represent changes in the material process and therefore the revenue. Case 4 suggests an increase of

25% resulting in a significant profit rise. The manual line would double the profit whereas the automated line experiences 40% more profitability. A material price drop of 25% in reverse significantly decreases profitability. A manual operation would barely make any profit while the automated line loses about 40% profitability.

As a result, this study shows that manual processes are sensitive to labor costs, complexity of the process design and of course, the material prices influencing the revenue. The fully automated line experiences significant changes according to the material price. Operational costs and line complexity do not influence profitability significantly. The semi-automated line is somewhere between both designed processes influenced mostly by the material price.

6 Conclusions

6.1 Summary of main findings

The analysis and interviews identify two key drivers for disassembling: vehicle design and disassembling technology. Both influence each other. While a design considering the recycling process can increase the utilization of materials that can be recycled with less need for separation, the development of an efficient disassembling technology can guide joint design and joining methods. Those cross-functional improvements are not present yet and therefore not applicable to ELVs for the next 20 years.

The development in battery disassembling demonstrates how current technological innovations can improve the circular approach. The motivation however is driven by the economic factor of the materials buried in end-of-life batteries, especially the rare metals, and the increasingly stringent regulations for battery systems. In the ELV vehicle shell the material value shows less potential compared to a battery, but regulations for ELVs are seen to motivate circular improvements soon.

Independent from the focus of this study on metals and especially steel with high purity and aluminum separated into its different alloys, the disassembling cannot be reduced just to the car body. The analysis shows that the interface between the first steps to recycling of an ELV and the disassembling process would be the authorized treatment facility after de-polluting and dismantling the ELV as shown in Figure 4 and Figure 5. The interior disassembly needs to be considered as well, whether both operations are done within the same facility or not. If not, the effort of logistics or intralogistics increase.

The performed business evaluation based on research and assumptions identifies the main drivers for a potential business. The standardization and automation of the disassembly process is one of the drivers, a disassembly concept should be applicable to several models and brands with a high degree of automation. The material market prices as the key value for the revenue stream is the other big influence. In this study the current material price is the baseline for the evaluations, but no prediction can be made from the analysis. The material price is one of the uncertainties with a high impact on potential business. According to the interview results, the scrap material price won't change higher purity from a disassembling process. The assumptions and statements are based on current technologies and process chains for recycling. If better purity allows to simplify recycling processes and the effect is scalable, the assumed revenue will increase to the benefit of a disassembling approach.

The analysis also shows that the current recycling approach without a disassembly and therefore contaminated material outcome after the shredding process is constantly improved by research and development with the target to optimize the identification and sorting of the post-shred material. This approach directly competes with the disassembly approach and is therefore another high impact factor with an uncertain future outcome. In the interviews the disassembling approach is still seen as more effective. Rough separation before the shredding process can avoid the checking and sorting of the entire material afterwards. However, there is no data from real cases and comparisons available and further studies should be carried out to generate some data.

Some vehicle manufacturers plan to remanufacture and reuse parts of the ELV in new vehicles, which is done in other industries as shown with the gas engines or railway industry. Most of the approaches focus on ELVs from the same manufacturer. This guarantees some standards but at least available information about the bill of materials and joining methods. Compared to the research question which does not limit the ELV disassembly to one manufacturer, this approach can be a first step to analyze and optimize the disassembly. In addition to the target of reusing parts, some manufacturers show practices to disassemble prototypes and cars of the same brand to remove interior and the wire harness and shred the rest of the car body for recycling. This method moves some process steps of the recycler to the manufacturer without the car body disassembling approach. The addition of car body disassembly for further purity of the material can be considered based on the outcome of this thesis.

The business evaluation in chapter 5.3 and the scenario analysis show that the introduction of disassembly lines involves a high investment. Especially the uncertain impact factors and resulting scenarios in chapter 5.2.3 highlight the risks associated with the investment, no matter which industry participant is looking into this business. The potential occurs when technologies are standardized, and supply chains are certain and consistent. The disassembling methods described in chapter 5.3.6 are technologies used in assembly lines and supporting tooling workshops today. The challenges of product and therefore process variances can technically be solved with vision technologies that are currently introduced in almost every industrial field. In addition, joining and design methods addressing both the component requirements and disassembly efficiency are researched as shown in chapter 2.4.3. Technology is simply available and the experience of an automotive supplier with the assembly of components is a valuable benefit when investigating the disassembly of ELVs.

As a summary Table 14 highlights the main impact factors for the implementation of ELV disassembling processes based on the findings from this thesis. There are technological challenges and economic risks introducing the disassembly process shown in chapters 5.2 and 5.3. The contribution to the circular economy as the ecological aspect of this study is highlighted in the right column of Table 14, indicating whether the impact factors influence CE positive or negative. The shown neutral contributions depend on the factor, whether it is high or low.

Table 14 Key impact factors for the implementation of end-of-life vehicle disassembling and the contribution to a closed loop vehicle lifecycle (created by the author)

Factor	**Impact on ELV disassembling strategy**	**CE**
	Technology	
Design variability	Complexity of disassembly and sorting technologies; challenges standardization	-
Joining methods	Feasibility of clean material separation	
Mech. fast.	Enable reversable assembly and clean separation	+
Welding techniques	Limited efficiency, similar filler alloys avoid contamination; No impact for materials that do not need to be separated	- +/-
Adhesive Bonding	Hinders disassembly if materials need to be separated; develop reversible adhesives	-
Alloy compatibility	Determines mixed scrap recycling effectiveness	+/-
Automation potential	Influences economic viability of disassembly versus shredding; drives scalability	+
Sorting development	Reduces need for disassembly; increases shredding and sorting material purity outcome	+
Design for disassembly	Increases disassembly efficiency; promote modular and mono-material designs	+
	Sustainability	
Utilization of recycled material	Lowers CO_{2eq} impact; high-purity recovery boosts carbon savings	+
Regulations	Can create long-term incentives for design and disassembly	+
	Economic	
Export trends	Reduces availability of recyclable materials; lack of supply	-
High labor and tooling costs	Encourages automation and standardization for scalable disassembly; drives investment decisions	-
Demand for purity	Drives depth and costs of disassembly	+
Scrap value	Drives investment decisions; push for sorting optimization	+/-
ELV logistics	Sourcing and transportation of ELVs challenge economics	-
Lack of data	Limits availability to define best practices or justify investments	-

6.2 Restate research question

This thesis explored the role of end-of-life vehicle disassembly according to the material purity outcome with the focus on potential technologies, ecological and economic aspects. The main target is the identification of the key impact factors and environmental conditions to follow the suggested disassembling approach.

The qualitative interviews with different stakeholders along the product lifecycle and expertise in different business units reveal some important insights contributing to the research question. The macro-environmental analysis and the identified impacts from the interviews are the baseline for the scenario analysis. As a result, the risks for an introduction of a disassembly process are determined. A brief business evaluation with multiple assumptions demonstrates the main impactors to generate economic benefit when introducing the disassembly process.

In summary the thesis describes the key drivers to answer the research question, how a disassembling process can contribute according to technical, ecological and economic aspects to a circular economy. However, to quantify the different aspects of the research question, more detailed studies would be necessary. The question can be answered with the identified contribution factors. Details to quantify each factor should be the subject of future research.

6.3 Critical discussion

The thesis identifies risks and concerns based on several uncertainties, especially according to the economic benefit when a new process is introduced in the current vehicle lifecycle. At the same time the thesis demonstrates opportunities with available technologies, technologies in research and best practices in different industrial areas. With the identification of the main impacts, detailed analyses for specific applications could follow using the concept and framework of this thesis as a baseline.

The logistic system to source ELVs and transport them from the ATF to the disassembling facility as well as the shipping of the sorted materials to the recycling facility is considered a concern in the interviews. The business evaluation in chapter 5.3 lists the process step but there are no costs associated with it due to the lack of data. Detailed application studies should deal with the costs for incoming and outgoing logistics.

The business evaluation based on assumptions also misses some potential value of neglected materials in this thesis. In the disassembly of the interior’s different plastics, fabrics and copper from the wire harness can get extracted and sorted. Mixed plastics might be lost for recycling, but some mono-material plastics can be recycled. The copper from the wiring has a certain value as well. Those values are not considered and are missing in this study.

The background analysis as well as the interviews show the need for collaboration between different stakeholders in the automotive industry. At the same time the competitive mindset hinders collaboration as discussed in the interviews. For the specific topic of disassembly, a strategic partnership with a recycling company would be beneficial. The thesis exposes the competition between the shredding and sorting, and the disassembly and shredding approach, but working together, the shredding processes can be optimized to the materials and components with the potential of energy saving. Less harder materials require less strength of the shredding device. Operating costs, including wear of the device, can be reduced if the processes are aligned between the disassembling and recycling company.

Besides the approach to generating more high-quality recycled materials, the usage of recycled metals in new vehicles needs to be described. The results show that the requirements of certain components of the vehicle would not allow any deviation from specified material characteristics. Therefore, the recycled material needs to provide homogeneous properties to be used in the car body design. As the thesis shows in several chapters, maintaining steel purity is the key aspect for reusable grades in new vehicles. Aluminum separated into different alloys can be recycled easier. Some automotive manufacturers already use upcycled aluminum which is recycled aluminum content mixed with raw materials to get to the desired material properties. Another approach would be the utilization of recycled materials in areas that won't require high performance for crashes or durability. The high safety requirements of a vehicle would not allow the utilization of recycled materials in every component, but based on the function of the part, an increased recycling content should be targeted.

According to the regional availability of ELVs to guarantee a consistent supply for disassembling, motivations like refund systems were discussed. The vehicle operator pays a deposit when purchasing the car and gets at for returning the ELV to an ATF the refund. In a timespan of ten to fifteen years and potentially different operators in between, this approach is more difficult than the bottle deposit system. But the disappearance of almost half of the potential ELVs in Europe advocates for some motivations and regulations in that matter.

6.4 Suggestions for future studies

The analyzed and suggested processes for the disassembly should be studied further to define the requirements of the process chain. Especially the separation processes defined as mechanical, or laser trimming should be investigated for feasibility on different car components. Different materials have an impact on operation speed as well as consumables and wear. Feasibility studies can adjust and refine the process layout. The recognition of parts, materials and geometry to guide the trimming tool for each ELV is another big topic to be studied for the feasibility of this application.

Logistics between the process steps need to be flexible for different vehicle brands and models. In addition, the fixture and clamping for the separation process need be flexible for the same reason. Different technologies can be studied to find variable options.

Technological studies improve the concept and therefore the business evaluation, especially investment and operation costs. An exemplary disassembly of an ELV based on the suggested process steps could demonstrate feasibility and suggest further process refinement and necessary investigations. In comparison to the shredding and sorting process with the same ELV model the outcome in terms of material and efficiency can be studied. The comparison was discussed and suggested during the interviews. This thesis shows a concept based on several assumptions from the performed analysis, which should be validated with some technological benchmarking data.

The design variability impacts the process variations of the disassembly. A comprehensive study of differences and similarities between different car designs per class and how they would impact the process chain could refine the process concept of a disassembly. In addition, the recognition of models and brands and a potential database on material content and joining methods can help to organize the production schedule of the disassembly as well as the process layout.

To sum up the suggestions, the thesis shows a concept and key drivers of a disassembling process and identifies areas with lack of data or general assumptions that can be turned into potential future studies.

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8 Appendix

8.1 Qualitative Interview Questions

General Understanding

1. Can you describe your experience with the circular economy, recycling processes in general, and end-of-life product disassembly?
2. What are the main challenges you face or foresee in implementing practices of circular economy in your industry?

Technological Insights Disassembly Process

1. Can you describe the main joining technologies currently used in your assemblies of steel and aluminum components?
2. Are any of these technologies designed with disassembly in mind?
3. Have you explored or implemented “design for disassembly” principles in your products?
4. What challenges do you see for the disassembling process?
5. What advancements in disassembly technology & design do you believe are necessary to improve the quality of recycled materials?

Sustainability Potential

1. How does your company currently calculate the carbon footprint of its products?
2. What role does material recycling play in your sustainability strategy?
3. How could disassembling end-of-life components and material harvesting contribute to reducing the carbon footprint of the product?
4. Are there any internal or external sustainability targets (e.g., OEM requirements, EU regulations) influencing your approach?
5. How would you describe the CO_{2eq} credit potential for providing sorted scrap back to material supplier?

Economic Benefits

1. What economic factors would motivate your company to invest in disassembly processes?
2. How could recovered materials (aluminum, steel) be reused internally or sold?

3. Are there existing partnerships or business models (e.g., take-back programs) that support this?
4. Can you share any examples of successful business models that integrate disassembly and recycling in the automotive industry?
5. What are the main cost drivers and savings potentials in disassembly vs. raw material sourcing?

Industry Collaboration

1. How can automotive suppliers collaborate with recycling companies and material suppliers to enhance circular economy practices?
2. What are the key factors that drive or hinder collaboration between different stakeholders in the automotive recycling chain?

Best Practices and Innovations

1. Can you provide examples of best practices from other industries that could be applied to automotive ELV disassembly?
2. What innovative approaches have you seen or implemented in your organization to support the circular economy?

Outlook

1. What do you see as the biggest barrier to implementing disassembly at scale?
2. What support (technical, regulatory, financial) would be needed to make this viable?
3. What do you think the future holds for circular economy practices in the automotive industry?

Final comments

8.2 Sensitivity Study

Calculation sheet and assumption for the different cases discussed in chapter 5.3.9. The assumptions for the baseline are based on the analysis of the thesis. Depreciation is assumed for seven years and the Weighted Average Cost of Capital considered at 9% for the automotive sector (Wirtschaftsprüfungsgesellschaft, 2025).

Factor	**Unit**	**Baseline**	**Case 1: Invest +25%**	**Case 2: Labor +25%**	**Case 3: Layout +25%**	**Case 4: Material +25%**	**Case 5: Material -25%**
Output in #	#	13,800	13,800	13,800	13,800	13,800	13,800
Weight ELV	t(ELV)	0.7	0.7	0.7	0.7	0.7	0.7
Eficiency	%	80%	80%	80%	80%	80%	80%
Output in t	t(ELV)	7,728	7,728	7,728	7,728	7,728	7,728
Revenue	EUR/ t(ELV)	€ 535	€ 506	€ 506	€ 506	€ 668	€ 401
Revenue per year	EUR	€ 4,131,389	€ 3,913,459	€ 3,913,459	€ 3,913,459	€ 5,164,236	€ 3,098,542
Labor costs	EUR/ h	€ 80	€ 80	€ 100	€ 80	€ 80	€ 80
OP costs manual	EUR/ h	€ 20	€ 20	€ 25	€ 20	€ 20	€ 20
OP costs auto	EUR/ h	€ 50	€ 50	€ 63	€ 50	€ 50	€ 50
Workdays per a	d	230	230	230	230	230	230
Workhours per a	h	1,840	1,840	1,840	1,840	1,840	1,840
Investment							
Manual Process	EUR	€ 300,000	€ 375,000	€ 300,000	€ 300,000	€ 300,000	€ 300,000
Auto Process	EUR	€ 500,000	€ 625,000	€ 500,000	€ 500,000	€ 500,000	€ 500,000
Heavy Duty	EUR	€ 500,000	€ 625,000	€ 500,000	€ 500,000	€ 500,000	€ 500,000
Scanning Process	EUR	€ 1,000,000	€ 1,250,000	€ 1,000,000	€ 1,000,000	€ 1,000,000	€ 1,000,000
Tools & Logistics	EUR	€ 3,500,000	€ 4,375,000	€ 3,500,000	€ 3,500,000	€ 3,500,000	€ 3,500,000
Weighted Average Cost of Capital	%	9%	9%	9%	9%	9%	9%
Depreciation	a	7	7	7	7	7	7
Manual Line							
Operators	#	16	16	16	20	16	16
Robots	#	0	0	0	0	0	0
Manual Seperation Process	#	11	11	11	14	11	11
Auto Seperation Process	#	0	0	0	0	0	0
Heavy Duty Auto process	#	0	0	0	0	0	0
Scanning Process	#	1	1	1	1	1	1
Tools & Logistics	#	1	1	1	1	1	1
Total Investment	EUR	€ 7,800,000	€ 9,750,000	€ 7,800,000	€ 8,700,000	€ 7,800,000	€ 7,800,000
Depreciation per year	EUR	€ 100,286	€ 125,357	€ 100,286	€ 111,857	€ 100,286	€ 100,286
Operational Costs per a	EUR	€ 2,944,000	€ 2,944,000	€ 3,680,000	€ 3,680,000	€ 2,944,000	€ 2,944,000
Profit per a	EUR	€ 1,087,103	€ 844,102	€ 133,173	€ 121,602	€ 2,119,950	€ 54,256
Payback	a	7.2	11.6	58.6	71.5	3.7	143.8
Semi-Automated Line							
Operators	#	10	10	10	13	10	10
Robots	#	2	2	2	3	2	2
Manual Process	#	10	10	10	13	10	10
Auto Process	#	1	1	1	1	1	1
Heavy Duty	#	0	0	0	0	0	0
Scanning Process	#	1	1	1	1	1	1
Tools & Logistics	#	1	1	1	1	1	1
Total Investment	EUR	€ 8,000,000	€ 10,000,000	€ 8,000,000	€ 8,900,000	€ 8,000,000	€ 8,000,000
Depreciation per year	EUR	€ 102,857	€ 128,571	€ 102,857	€ 114,429	€ 102,857	€ 102,857
Operational Costs per a	EUR	€ 2,024,000	€ 2,024,000	€ 2,530,000	€ 2,668,000	€ 2,024,000	€ 2,024,000
Profit per a	EUR	€ 2,004,532	€ 1,760,888	€ 1,280,602	€ 1,131,031	€ 3,037,379	€ 971,684
Payback	a	4.0	5.7	6.2	7.9	2.6	8.2
Automated Line							
Operators	#	0	0	0	0	0	0
Robots	#	15	15	15	19	15	15
Manual Process	#	0	0	0	0	0	0
Auto Process	#	10	10	10	13	10	10
Heavy Duty	#	1	1	1	1	1	1
Scanning Process	#	1	1	1	1	1	1
Tools & Logistics	#	1	1	1	1	1	1
Total Investment	EUR	€ 10,000,000	€ 12,500,000	€ 10,000,000	€ 11,500,000	€ 10,000,000	€ 10,000,000
Depreciation per year	EUR	€ 128,571	€ 160,714	€ 128,571	€ 147,857	€ 128,571	€ 128,571
Operational Costs per a	EUR	€ 1,380,000	€ 1,380,000	€ 1,725,000	€ 1,748,000	€ 1,380,000	€ 1,380,000
Profit per a	EUR	€ 2,622,817	€ 2,372,745	€ 2,059,888	€ 2,017,602	€ 3,655,665	€ 1,589,970
Payback	a	3.8	5.3	4.9	5.7	2.7	6.3