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Disassemblability Assessment of Car Parts: Lessons Learned from an Ecodesign Perspective

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Abstract: A conventional vehicle requires more than 50 different metals in its manufacturing, most of which are critical. Given this circumstance, enhancing sustainability from a raw materials perspective requires improvements in the disassemblability of car parts. This enhancement aims to yield metal-rich fractions, enabling the application of effective recycling processes for the recovery of critical metals. This helps avoid the downcycling that occurs in conventional shredding processes. The present study was undertaken to analyze the challenges associated with disassembling components of significant value due to their metal content. The methodology comprises two distinct main stages: an identification of critical car parts and an assessment of disassemblability. The selection of car parts was determined by the criticality of each one through the thermodynamic rarity indicator. Disassemblability was studied experimentally, encompassing three different levels. This classification defines the stages from extracting parts from the vehicle and obtaining recycling fractions in their purest form: ferrous metals, aluminum, non-ferrous metals excluding aluminum, and plastics. This methodology was implemented on two vehicles manufactured by SEAT: SEAT Leon models II and III. As a result, not only was disassemblability information about these car parts collected, but several ecodesign recommendations were also identified as valuable guidance for future designs, specifically aimed at enhancing metals' recyclability. In conclusion, it must be acknowledged that contemporary vehicle design often prioritizes cost-effective manufacturing processes. However, this approach may compromise the disassemblability and recyclability of the product. The ongoing transition to electric vehicles necessitates a re-evaluation of design principles, particularly from the perspective of the circular economy.

Keywords: circular economy; disassemblability; thermodynamics; ecodesign; resource efficiency; recyclability

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1. Introduction

The vehicle manufacturing sector is one of the largest raw material consumers [1], and the tendency is that this demand will grow in the future. Global passenger car (hereinafter referred to as cars) sales have doubled in the last 30 years [2]. For instance, in the EU alone, the passenger car fleet has grown by 15.9% from 2012 to 2021 [3] and will continue to grow in the coming years [4]. This evolution in the vehicle fleet will at the same time bring an increase in raw material demand needed to manufacture them [5]. In recent years, not only the quantity but also the type of raw materials required to manufacture vehicles has changed [6]. For example, permanent magnets composed of rare earths are used to manufacture electric powertrains [7]. Other metals such as lithium, cobalt, nickel, or manganese are used to manufacture batteries [8] and semiconductors to create electronic components [9]. Moreover, the highest part of these type of metals are considered to be critical due to potential supply problems or the increasing importance for economic development, as is evidenced by the periodical report about critical raw materials published by the European Commission [10]. Supply risks of certain materials are a serious threat in the automotive sector. This is especially true with the mass introduction of fully electric vehicles, which are very dependent on some of these critical metals.

Focusing on end-of-life vehicle (ELV) recycling processes, they are typically aimed at isolating hazardous contents; selling spare parts; recovering and recycling some regulated parts, like batteries, tires, or catalytic converters; and recycling metals existing in the largest quantities, such as steel and aluminum alloys [9]. However, as has been mentioned before, a vehicle incorporates many more metals than those that are currently being recycled [6], and most alloy elements are lost [11] either because they are downcycled or because they end up in the automobile shredder residue (ASR), ultimately becoming landfilled. Metal downcycling in ELV processes is a topic of concern; previous research studies have analyzed the downcycling of different materials such as steel alloying elements [12], nickel [13], or aluminum [14].

One of the solutions to improve the recycling of critical raw materials is to disassemble the car parts that incorporate these metals to then apply specific recycling processes based on metallurgical operations [15]; thus, the scope of this work is to perform a disassemblability assessment of car parts. This work is of great importance for conventional combustion engine vehicles but will be even more relevant for electric vehicles. As was evidenced by Milojevíc et al. [16], the disassemblability of electric cars must evolve towards new disassembly plants. In the pursuit of advancing sustainable practices in disassemblability to promote product sustainability and circular economy principles, numerous studies have explored innovative approaches. The following is the state of the art of the research.

From a disassemblability methodologies perspective, Parsa et al. [17] investigated a disassembly method centered on human–robot collaboration, effectively combining human flexibility with robotic repeatability and accuracy. The study employed an automotive fuel pump as a case study. Along this line, Rehal and Sen [18] explored disassembly from a sequence scheme perspective, introducing a shell assembly method to enhance assembly accessibility and reduce disassembly time. Liu et al. [19] proposed a solution to improve smartphone disassemblability for waste prevention, studying five smartphone models and suggesting methods to enhance efficiency in disassembling large quantities.

Regarding disassemblability oriented towards repairability, Ruiz-Pastor and Mesa [20] introduced an index for assessing product repairability based on assembly and disassembly complexity. Utilizing a coffee machine as a case study, the method identified aspects for redesigning. Moreover, Rodriguez et al. [21] explored disassemblability as a key element to promote repairability, providing ecodesign guidelines based on the analysis of an electric oven.

Cappelletti et al. [22] conducted a valuable review on the de-manufacturing concept, emphasizing barriers hindering circular economy goals. Special attention was given to disassembly, re-manufacturing, and de-manufacturing, with cost being identified as a critical obstacle. Favi et al. [23] compiled disassembly knowledge from dismantling centers to design measures aimed at improving the end-of-life phase for electronic products, supporting companies in designing products with enhanced repairability.

Regarding disassembly applied to specific products, Zahedi et al. [24] investigated aircraft disassemblability, focusing on minimizing disassembly time and effort, and improving output material quality for post-disassembly processing. Sawanishi et al. [25]

analyzed the feasibility of reusing mobile phone components, particularly focusing on liquid crystal displays, demonstrating that component reuse is feasible through design for disassembly. Germani et al. [26] analyzed disassemblability to promote closed-loop scenarios at a product's end of life, calculating disassembly time based on product structure and component liaisons, using a combination oven as a case study. Sabaghi et al. [27] studied a jet aircraft from a disassemblability perspective, aiming to obtain a disassembly model and calculate a disassemblability index. Kroll and Carver [28] examined the evaluation of disassemblability for recycling, proposing a method to estimate disassembly time during the design stage, using an electric drill as a case study. Vanegas et al. [29] proposed a method to calculate disassembly time based on the Maynard operation sequence technique, validated using a liquid crystal display monitor, offering a tool for designers to improve product designs. Milojevíc et al. [30] researched the disassemblability of a bus dashboard constructed using ecological materials. Giudice and Kassem [31] introduced a structured method for analyzing and reconfiguring the disassembly depth distribution of components within a constructional system, applied to a video-entryphone module. Finally, Talens Peiró et al. [32] applied European legislative ecodesign policies to enterprise servers, investigating designs for disassembly requirements.

In the case of modularity assessment oriented towards disassemblability, Romano et al. [33] analyzed the modularity of power electronic converters, emphasizing design modularity as a key factor for encouraging disassemblability. The study concluded that enhancing modularity can contribute to circularity. Soh et al. [34] proposed a conceptual framework for product designers to prioritize design for disassembly guidelines, enhancing efficiency in retrieving high-value cores for remanufacturing, which was validated using an electronic linear actuator.

From the perspective of tools to assess and improve disassemblability, Smith and Chen [35] presented a rule-based recursive method for optimizing disassembly sequences from an ecodesign perspective, applied to a power brake, concluding that complete disassembly is often impractical for a few components. Go et al. [36] provided a review of disassemblability evaluation methods applied to automobiles, emphasizing the need for effective disassembly methods to enhance product recovery. Desai and Mital [37] proposed a comprehensive methodology to enhance product disassemblability, assigning time-based numeric indices to design factors for a quick determination of disassembly time. After analyzing the state of the art, it is evident that there is an urgent need to address the current disassembly capacity of the critical components used in the current vehicles.

This work addresses the need to improve the disassemblability of car components for recycling as well as the need to encourage the mandatory recycling of certain electronic components in a specific way and not having them be fragmented with the rest of the car. As a result, disassemblability recommendations are presented. These recommendations are useful from an ecodesign perspective to be considered for vehicle designers or policy makers. Moreover, the guidelines are delineated with the objective to facilitate the disassembly processes in end-of-life treatment facilities. It is crucial to underscore that these facilities predominantly consist of small- to medium-sized enterprises (SMEs) or familial enterprises operating within stringent knowledge or technical resource constraints. Notwithstanding these limitations, their pivotal role in the retrieval of materials, such as catalytic converters or batteries, is undeniable, as they are tasked with the disassembly of said components from ELVs. Consequently, a meticulous examination of disassemblability is imperative from the vantage point of those tasked with its execution, ensuring the efficient routing of components to recycling centers utilizing metallurgical processes.

To achieve this, we conducted disassemblability experiments on two actual vehicles, assessing their most critical components. These components were selected based on the critical materials used, which is measured through the concept of thermodynamic rarity. This work represents the first research initiative on disassemblability conducted on complete vehicles from two different generations. This approach not only facilitates the study of disassemblability but also provides insights into the evolution of vehicle design from this perspective.

2. Materials and Methods

2.1. Taxonomy about Disassemblability

A study on disassemblability and its difficulty requires a definition and classification of the main terms used. For this purpose, the following concepts were adopted during the research:

Part: It is a car's component with a code number. Parts can be usually purchased in vehicle spare part stores. An example is a headlight.

Subpart: It is a component that belongs to a main car part. These parts may (or may not) own code numbers, so they cannot be purchased in the aftersales market. Subparts are usually part of a larger assembly, which is the part. An electronic board, a small electrical engine or a plastic cover can be considered as examples of subparts. Following the headlight example, a subpart would be the transparent casing.

Disassembly: A group of tasks that are executed sequentially with the aim to dismantle a part from a car without breaking any other part. After this activity, any car part can be reused again. In this way, it is possible to achieve the disassemblability level 1. Following the headlight example, the disassembly would be the tasks group needed to dismantle it from the car.

Subdisassembly: Group of tasks to dismantle a car part into subparts. Subdisassembly operations must only be applied if the car part is designed to be subdisassembled. This happens when bolted joints or clips are used. In this sense, those subparts which are glued or joined by thermal methods are not considered as subdisassembly. Subdisassembly operations can be applied in cascade so that a subpart can be subdisassembled into further subparts. In this way, it is possible to move from disassembly level 1 to 2 or from 2 to 3, being that these levels are differently achieved by disassembly operations. In the case of a headlight, they would be the operations to dismantle the bulbs, housings, transparent casing, wiring, or reflector shades.

Figure 1 represents an example of these levels; each of them are explained below.

Figure 1. Disassemblability levels. Example based on a combi instrument and SEAT León II.

Level 1: Disassembly of the main parts from the vehicle. In this level, the car part is disassembled from its location in the vehicle. (See Figure 1 example: the combi instrument is dismantled).

Level 2: Subdisassembly of the main parts into smaller subparts (if possible). In this level, the car part is subdisassembled into smaller subparts. This operation is performed out of the vehicle using a workbench. (See Figure 1 example: the combi instrument is dismantled in plastic covers, electronics, display, screws, and the display frame).

Level 3: It classifies subparts achieved in level 2 into recycling groups with the aim to obtain as pure as possible streams: ferrous metals; non-ferrous metals excluding aluminum; aluminum and plastics. It must be noted that it is not always possible to have all fractions due to the achieved subparts sometimes being a mix of different ones. (See Figure 1 example: disassembled subparts are classified in three material fractions).

The purpose of achieving these fractions is to have a high degree of metal recovery in specific recycling processes based on metallurgy. As explained by Iglesias-Embil, M et al. [15], who applied metallurgical processes to recover critical metals from electronic car parts, current metallurgical recycling processes require taking one of these fractions as a starting point.

After explaining the terminology and disassembly levels used, the main phases of the research are described. The present work involves two distinct main stages. The first stage entails the selection of the most critical car parts on which the disassemblability analysis is subsequently performed. This process commences by analyzing the material composition data of all car parts, from which the criticality of each one is calculated using a thermodynamic approach. Once the critical car parts are selected, an experimental disassemblability activity is conducted using two vehicles to identify ecodesign recommendations. The following sections provide detailed information regarding each stage.

2.2. Selection of Representative Cars

Two distinct car models were selected based on the following criteria: (1) representativeness of the models concerning the total sales of the brand; (2) different model generations considering their age; and (3) being the same model but of different generations to analyze the evolution of disassemblability along the lifetime. Following these criteria, SEAT Leon generation II and III models were chosen. Due to their age, these models were only equipped with internal combustion engines. From the size point of view, they can be classified as segment C and hatchback bodies, being one of the most sold and therefore representative types of vehicles in Europe.

From a brand point of view, this model was the best seller from 2019 to 2021, achieving around half of the total brand´s sales. Regarding age, the analyzed car generations span a production period of 15 years, from 2005 to 2012 for SEAT Leon II and from 2012 to 2020 for SEAT Leon III. Finally, it is highlighted that these models are the typical ones that are achieving the end-of-life (ELV) currently or will reach it in the coming years. Therefore, the results of this study are more valuable due to its application.

Once the vehicles were selected, the following two activities were conducted. The first one was to configurate these vehicles in an internal information technology system MISS (Material Information Sheet System). This system belongs to the Volkswagen Group and is the interface with IMDS (International Material Data System), in which all automotive suppliers are obliged to declare the composition and weight of the parts under their responsibility. As a result, the theoretical material composition of each car as a whole and of each car part in particular was calculated. The second activity was to assess the disassemblability. To this aim, the company Industrias Lopez Soriano (ILSSA), specializing in ELV recycling, provided two operational vehicles for conducting the experimental activities. Information about the vehicles used in the experimental activities is included in Appendix A (Table A1).

2.3. Thermodynamics as a Tool to Identify the Most Critical Car Parts

As demonstrated by Ortego and coauthors [6] a mass-based assessment of metal content in a vehicle does not promote the recycling of scarce and minor metals like those used in electronic components. As a consequence, this work proposes a more equitable approach, where an alternative indicator based on the second law of thermodynamics and the exergy concept was used. This indicator, termed thermodynamic rarity, aims to assign a physical value to minerals based on two parameters: (1) their relative abundance in nature and (2) the net energy required to extract and process them after obtaining the refined metal from the mine. Thermodynamic rarity combines the advantages of mass and economic-based approaches, being a strictly physical indicator that is universal, objective, and more stable than monetary approaches. For this reason, this work proposes such a method for the identification of the most critical components.

Thermodynamic rarity values for the 50 metals analyzed in this study are included in Appendix B (Table A2). Such values are used as weighting factors for each metal used in a car to identify the most critical vehicle components. This method has already been published and applied to automobile sector [38], and given its effectiveness, it was also used in the present work. It is not part of the scope of this work to deal with the methods to assess the criticality of materials. However, a brief description of the method is presented below.

The identification of critical components is performed by using two thermodynamic indicators: thermodynamic rarity [kJ] and rarity intensity [kJ/g]. The first one has been previously explained in detail, and the second one also considers the thermodynamic value with respect to the weight of the component. The second allows us to identify those components that, despite having little weight, have a high concentration of valuable metals with respect to their total weight. To apply this methodology, first, the material composition of cars was achieved by using the MISS tool. Detailed information about this system cannot be presented for confidentiality issues. Once the elemental composition of every vehicle is provided, the thermodynamic rarity of each car part can be obtained by applying Equation (1):

$$Rarity\ (A) = \sum_{i=1}^{n} m(i) \cdot Rarity\ (i) \quad (1)$$

where m_i is the mass content of a given element expressed in grams of the selected component i and R_i is the thermodynamic rarity of that specific element (in kJ/g). It should be noted, however, that the quantity of iron and aluminum contained in vehicles has been initially removed. This significant mass contribution does not allow us to clearly see the criticality of other used metals because their weights are several orders of magnitude lower. Moreover, such minor metals are often not functionally recycled but become downcycled with iron and aluminum (i.e., incorporated in minor quantities in the matrix of iron or aluminum blocks with no functional use). As has been mentioned before, it is not only essential to obtain the thermodynamic rarity of each car part, but also the rarity intensity.

To calculate this indicator, Equation (2) is applied:

$$Rarity\ intensity\ (A) = \frac{R(A)}{\sum_{i=1}^{n} mi} \left[\frac{kJ}{g}\right] \quad (2)$$

where R(A) is the rarity measured in kJ/g of the car part "*A*" and m_i, the specific mass of element i in car part A.

Once the thermodynamic assessment was carried out, the final selection of "critical" car parts was performed, considering the following criteria: (1) thermodynamic rarity and rarity intensity values; (2) the current absence of specific recycling processes for these parts; (3) the interest of SEAT to research these car parts; and (4) to assess different type of electronics: sensors, actuators, LEDs, or screens.

2.4. Disassemblability Assessment

Disassemblability activities were performed in MotorLand´s Aragon facilities. MotorLand Aragon is a Technology Center located in Spain that includes development tracks and specialized facilities for vehicle development. Appendix C contains information about the tools and facilities used (Figures A1 and A2). For each disassembly level, data sheets were compiled with information about the process. Table 1 shows the information gathered in each level.

Table 1. Information collected in disassembly and subdisassembly processes.

Information	Description	Disassembly Level
Location	It describes the vehicle zone (inside, outside, front, lateral, rear) where the part is located.	1
Is it very exposed in case of an accident?	This information is essential to know if this part can also be disassembled in case an ELV comes from an accident.	1
Parts to be disassembled before	It is used to determine the accessibility of the part.	1
Time (min)	It is calculated according to the results achieved in MotorLand facilities.	1–2
Required tools	It shows not only how many tools are required but also if they are standard or not. Sometimes, manufacturers design specific tools for the disassembly of some parts, which makes their disassembly difficult.	1–2
Number of people needed to disassemble	It considers how many people are needed to disassemble or subdisassemble the car part or subpart.	1–2
Process description	It is a narrative description of the main operations developed to disassemble the part.	1–2
Main type of material fraction	It describes if, once a subpart is subdisassembled, it can be classified into a specific recycling fraction: ferrous, non-ferrous excluding Al, aluminum or plastic.	3

Regarding the time spent in disassemblability and subdisassemblability operations, it is important to remark that these activities were led by a professional researcher and car mechanic, the owner of Dynasty Motors, a vehicle repair and restoration company (https://www.dynastymotors.eu/). Moreover, he was also assisted by theoretical information on the component disassembly processes supplied by Centro Zaragoza (https://web.centro-zaragoza.com/es), an expert research center in vehicle repair located in Spain. So, the disassembly processes were executed in an optimized and professional manner.

With the information gathered, the term "*difficulty level*" was defined for the purpose of assigning a degree of labor to the operations required for disassembly or subdisassembly. To this end, three criteria were considered. The first one, "*number and type of tools needed*", takes into consideration how many tools are required to disassemble the part and if these tools are standard or are specific tooling designed by the manufacturer. The second one, "*number of parts to be disassembled before*", analyses how many parts must be disassembled before the main car part. It gives an idea about the accessibility of the part. Finally, the third one, "*are 2 or more people required?*", considers the difficulty degree if more than one person is needed to disassemble the part. Knowing this information, the difficulty level is calculated as a result of these criteria and considering the Boolean logic represented in Table 2.

Table 2. Difficulty level criteria.

Difficulty Level	Number and Type of Tools Needed	Boolean Operator	Number of Parts to Be Disassembled before	Boolean Operator	Are 2 or More People Required?
High	>5 OR non-standard	OR	>3	OR	YES
Medium	[2–5]	AND	[1–3]	AND	NO
Low	1	AND	0	AND	NO

3. Results

3.1. The Most Critical Car Parts

After assessing the criticality of all car parts and considering the absence of specific recycling processes, the following components were identified as critical: infotainment, combi instrument, exterior mirrors, additional brake lighting, speed sensor, rain sensor, and air quality sensor. An in-depth study of the disassemblability of these seven components was conducted, although in the process, more car parts were also researched. Table 3 illustrates the material composition of these parts, along with their criticality in thermodynamic terms.

Table 3. The most critical car parts.

Part	Model	Thermodynamic Rarity (kJ)	Rarity Intensity (kJ/g)	Weight (g)	The Most Critical Metals and Their Contribution to the Thermodynamic Rarity			
Infotainment	Leon II	582,581	295	1973.99	Ta 57.14%	Pd 26.11%	Au 7.04%	Cu 5.21%
	Leon III	538,665	386	1394.82	Ta 64.34%	Au 18.41%	Pd 5.45%	Cu 4.94%
Combi instrument	Leon II	683,023	823	829.89	Au 53.56%	Ta 36.29%	Pt 6.22%	Ag 1.06%
	Leon III	269,510	367	733.43	Ta 76.15%	Au 8.42%	Pd 6.42%	Cu 5.44%
Exterior mirrors	Leon II	37,544	40	928.38	Zn 64.49%	Cu 31.13%	Mg 1.32%	Ni 1.01%
	Leon III	209,219	181	1156.13	Ga 54.47%	In 31.20%	Cu 5.92%	Au 2.43%
Additional brake lighting	Leon II	17,700	207	85.55	Au 53.25%	Ta 37.64%	Pt 6.22%	Cu 1.26%
	Leon III	31,345	354	88.4	Ta 73.92%	Au 8.21%	Pd 6.23%	Cu 5.06%
Speed sensor	Leon II	4548	451	10.08	Au 91.40%	Cu 3.95%	Pd 3.84%	Sn 0.32%
	Leon III	4548	451	10.08	Au 91.40%	Cu 3.95%	Pd 3.84%	Sn 0.32%
Rain sensor	Leon II	NA						
	Leon III	7124	431	16.52	Ta 74.47%	Au 7.29%	Pd 6.28%	Cu 5.94%
Air quality sensor	Leon II	NA						
	Leon III	4922	347	14.19	Ta 76.97%	Au 7.68%	Pd 6.47%	Cu 5.62%

NA: Not available in this model.

The components cover a wide range of components, including light emitting diodes (LEDs), sensors, electronics, displays, and electric drives. As is evident, all components are electronic in nature. However, due to the absence of specific recycling mandates, such as those for batteries or catalytic converters, these components often undergo recycling processes primarily designed for steel and aluminum. Consequently, the primary materials they utilize, in terms of mineral resources, end up being downcycled.

Among the elements that contribute significantly to thermodynamic rarity, Ta is utilized in various electronic components, primarily for capacitor manufacturing. Additionally, Au and Ag are present in several parts due to their utility in forming electrical contacts and soldering, respectively. Notably, Pt and Pd are also used in electronics for the production of multilayer capacitors. Furthermore, it is worth highlighting the differences observed in rear-view mirrors. In the case of the Seat Leon III, its thermodynamic rarity is 209,219 kJ compared with 37,544 kJ for the Leon II. This discrepancy arises from the fact that the Leon III incorporates a turn signal in the rear-view mirror, necessitating high-value semiconductors for LED lighting, such as Ga or In. Finally, it must be considered that the SEAT Leon II did not have the possibility of being equipped with air quality and rain sensors.

3.2. Disassemblability Assessment

After identifying the critical components, a disassembly study was conducted. The initial phase of the study involved analyzing the first disassembly level, which focused on dismantling the part from the vehicle. The key findings are presented in Table 4.

Table 4. Main results of the disassemblability assessment (Level 1) over the critical car parts.

Car Part	Model	Is It Very Exposed in Case of an Accident?	Parts to Be Disassembled before	Average Time (min)	Required Tools	Difficulty Level
Infotainment	Leon II	NO	NO	10 min	Non-standard	High
	Leon III	NO	NO	10 min	Non-standard	High
Combi instrument	Leon II	NO	YES	9 min	Standard	Medium
	Leon III	NO	YES	9 min	Standard	Medium
Exterior mirrors	Leon II	YES	YES	50 min	Standard	Medium
	Leon III	YES	YES	12 min	Standard	Medium
Additional brake lighting	Leon II	NO	NO	5 min	Standard	Low
	Leon III	NO	NO	5 min	Standard	Low
Speed sensor	Leon II	NO	YES	10 min	Standard	Low
	Leon III	NO	YES	10 min	Standard	Low
Rain sensor	Leon II			NA		
	Leon III	NO	YES	7 min	Standard	Medium
Air quality sensor	Leon II			NA		
	Leon III	NO	YES	21 min	Standard	Medium

NA: Not available in this model.

There is only one part, the exterior mirror, that is usually exposed in case of an accident; as a consequence, it may not be disassembled in case the ELV comes from an accident. Nevertheless, the other parts are protected and should be available for subdisassembly, even if the car reaches the ELV after an accident. The average disassembly time is 11 min. There is only one part in the SEAT Leon model II with a quite high disassembly time (exterior mirrors—50 min). This is a consequence of the front lift motor location. Removing exterior mirrors requires the disassembly of door panels in any model. Nevertheless, in this model, the lift motor is located inside the door plastic panel instead of inside the door metal body. As a result, removing the door panel is more complicated than in the other cases. Finally, it is highlighted that only one part (infotainment used in SEAT Leon model II and SEAT Leon model III) requires non-standard tools for the disassembly process, so in this case, the difficulty level can be considered as high due to it being unable to be removed with conventional tools such as screwdrivers or torx wrenches.

After level 1, the subdisassemblability was researched (Level 2). The main results of this stage are included in Table 5.

There was only one component that could not be further disassembled into smaller parts—the speed sensors. This is because the electronics are encapsulated together with the cover in a single indivisible part. In all other instances, the disassembly difficulty was low, requiring only standard tools. Finally, we analyzed the type of material of each subpart. This task is quite important because the main aim of the process is obtaining homogeneous material fractions to apply in later specific recycling processes. Table 6 shows the fractions obtained and if a mix of different fractions was presented in any subpart.

Table 5. Main results of the disassemblability assessment (Level 2) over the critical car parts.

Car Part	Model	Average Time (min)	Required Tools
Infotainment	Leon model II Leon model III	<10 min <10 min	Standard Standard
Combi instrument	Leon model II Leon model III	<5 min <5 min	Standard Standard
Exterior mirrors	Leon model II Leon model III	<5 min <5 min	Standard Standard
Additional brake lighting	Leon model II Leon model III	<1 min <1 min	Standard Standard
Speed sensor	Leon model II Leon model III	NP NP	NP NP
Rain sensor	Leon model II Leon model III	<1 min <1 min	Standard Standard
Air quality sensor	Leon model II Leon model III	NA <1 min	NA Standard

NA: Not available in this model. NP: It is not possible to disassemble.

Table 6. Main results of the disassemblability assessment (Level 3) over the critical car parts.

Car Part	Model	Non-Ferrous Metals Excluding Al	Al	Ferrous Metals	Plastics	Mix of Fractions
Infotainment	Leon model II	X	X	X	X	
	Leon model III	X		X	X	fm—nfm—p
Combi instrument	Leon model II	X		X	X	
	Leon model III	X		X	X	nfm—p
Exterior mirrors	Leon model II			X	X	
	Leon model III			X	X	fm—nfm—p
Additional brake lighting	Leon model II	X			X	
	Leon model III	X		X	X	
Speed sensor	Leon model II					fm—nfm—p
	Leon model III					fm—nfm—p
Rain sensor	Leon model II	X		X	X	
	Leon model III	X		X	X	
Air quality sensor	Leon model II					
	Leon model III	X			X	

fm: Ferrous metal; nfm: non-ferrous metal; p: plastics.

The separation degree achieved for the different fractions varies according to the given car part. For example, the infotainment used in the SEAT Leon model II has a subpart (CD reader) that cannot be subdisassembled. Consequently, a mix of ferrous, non-ferrous metals, and plastics is left. This fact is shown in Figure 2.

In the case of the combi instrument used in the SEAT Leon model III, the information displayed is joined with the cover and, consequently, there are fractions of non-ferrous metals with and without Al that cannot be separated. Finally, the case of the exterior mirrors in the SEAT Leon III is highlighted. Figure 3 contains the different subparts where there are a mix of material fractions. These subparts are: the thermal mirror, wiring, LED lighting, and automatic adjustment system.

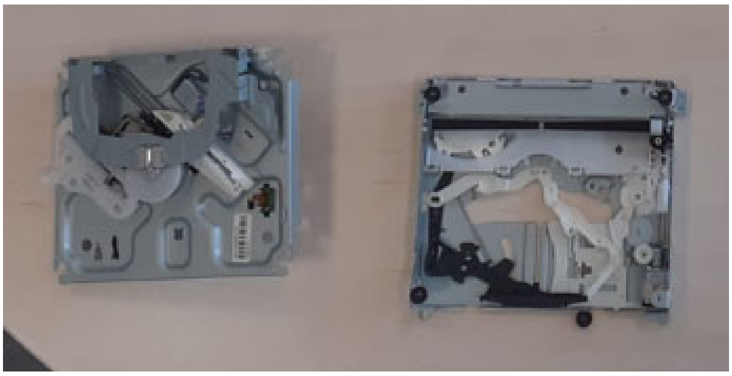

Figure 2. Subpart of a CD reader that cannot be subdisassembled in specific recycling material recycling fractions.

Figure 3. Several subparts of the exterior mirror.

These cases in which there are heterogeneous fractions of materials represent a barrier to disassembly, as it makes no sense to carry it out if it is not possible to easily reach a specific metal concentrate to be latterly recycled.

3.3. Valuable Insights toward Ecodesign Recommendations

As mentioned earlier, in addition to thoroughly studying the most critical car parts, the experimental disassembly process involved examining the vehicles as a whole. The following conclusions were drawn from an ecodesign perspective.

The use of glues to join some parts is very extensive. For example, glue is used in the front headlight to join the transparent front case with the main lighting body. Consequently, these two components cannot be separated, and all metals used in the reflector must be sent to recycling with the plastics case, which reduces the efficiency of recycling from a metal recovery perspective.

Thermal rivets are also very extensive and should be avoided when possible. For example, in the case of on-board units, the electronic boards are joined to the plastic cases using this union method. This fact makes the separation of the two main fractions (non-ferrous metals excluding Al and plastics) non-feasible.

The case of the LEDs used in some lightings must also be improved. Rear light clusters that use LEDs cannot be subdisassembled. As a result, the recycling fraction is a mixology of non-ferrous metals and plastics. On the other hand, this design does not allow for any reparation possibility.

Sometimes, the designs evolved in such a way as to hinder repairability. The case of the front window lifting mechanism is a clear example. In the SEAT Leon model II, the door panel contains the electrical engine and the driving mechanism. Consequently, an easy task such as removing the door panel needs nearly 1 h of work. This fact highly hinders the disassembly of valuable parts such as exterior mirrors, door units, or lift motors.

In the SEAT Leon model II, the front window cleaner system needs two engines. This is a consequence of a design that is more oriented towards aesthetical reasons than performance reasons. In this model, the wiper arms are moved in opposite directions, and two engines are needed. In the following model (SEAT Leon model III), the design with a single motor was adopted, thereby reducing the number of critical parts.

Electronic units are usually accessible as ECUs or onboard units. However, the accessibility of airbag units should be improved. These units are placed under the dashboard, requiring around 20–30 min of disassembly time.

Another positive fact stated has been the design of the combi instrument. In the past, it was the norm that the steering wheel and the airbag had to be removed before accessing the combi instrument. However, in the studied models, this operation was reasonably straightforward.

The use of non-standard tools was only required in the disassembly of infotainment units used in the SEAT Leon model II and SEAT Leon model III. It is recommended to apply a system similar to other models where torx screws are used.

Generators and starter motors are two relevant parts from a raw materials perspective because of the high content of copper and rare earths. It would be advisable to remove both parts from the car before shredding. Both parts could be retrofitted and used again in new cars or aftersales markets. Finally, the location in the engine area makes the disassembly task more difficult than for other parts located elsewhere. However, there is still room for improvement. For instance, the generator should be in the upper part of the accessory belt instead of the lower part. This way, it would be more accessible from the top of the engine and could be removed without the use of a lift.

In the case of exterior mirrors, which are very valuable from a material point of view, the design should be oriented towards disassembling them from the exterior side instead of from the interior, where the interior door panel needs to be disassembled. This situation also happens with front lights. As it is now, bumpers or wheel covers need to be removed, making this operation unfeasible from a recyclability point of view.

4. Discussion

It is important to consider that disassembly operations can be applied to the majority of ELVs. Usually, a car arrives at its end-of-life stage because of two reasons: (1) because of obsolescence, which happens when the car's age is around 11 years (the average EU vehicle age is 10.8 years according to the Spanish automobile manufacturers association (ANFAC) data consulted on 4 December 2023) and (2) because of an accident, a case where reparation costs are usually higher than the car's intrinsic value. In the second case, some parts will not be able to be disassembled, either because of damage or because of difficulty in accessing them. For this reason, statistical research has been performed using an internal database from the ILSSA to check the number of cars that reached the end-of-life for both reasons. Considering a sample of ELVs managed by the ILSSA from 2018 to 2021, from an overall amount of 4483 ELVs, 170 came from accidents (3.79%). As has been mentioned before, in the cases of vehicle accidents, disassembly operations are complicated or even impossible. However, this is a small percentage of cases compared with the total. Accordingly, the results of this work are focused on obsolete ELVs and should be considered the norm.

The obtained results are of great value as they highlight the existing barriers to reduce downcycling occurring in current ELV recycling processes. This study has been conducted for vehicles of a specific brand, which is part of the VW group, meaning that there are numerous models within that group sharing components and designs with the analyzed ones. Although a group of mainly electronic parts have been analyzed, it is important to highlight that there are other pieces that are also fragmented and have a significant value due to the materials they use. Examples of these parts are starter motors or alternators. In addition, they also have a high repairability for reuse in used or new vehicles.

However, it should be noted that ecodesign recommendations are based on experiments conducted with the specified vehicles. Therefore, it cannot be guaranteed that they are universally applicable to other brands or models. On the other hand, it is also important to highlight that, at times, ELVs may have been altered or modified by their owners in a manner that prevents the application of disassembly operations as theoretically estimated.

This work addresses its initial target; with a small selection of car parts, it becomes evident that small efforts in design—oriented towards disassemblability—would make certain components more recyclable. Moreover, as a result, it has been possible to define ecodesign recommendations to this aim. This work constitutes an advancement in knowledge made due to the selection of more critical car parts in a vehicle as a whole. Over these car parts, a disassemblability and subdisassemblabiliy assessment has been performed using two functional hatchback segment C vehicles, which are representative of the typical ones that are achieving the end of the life now or will reach it soon.

Further work remains to be conducted to quantify the improvement in disassembling components for the application of specific metallurgy-based recycling processes. The objective of this research should be to measure how much mineral capital can be recovered through disassembly and recycling compared with the current situation. It would also be very useful to study the role of automation and 4.0 technologies such as cobots to perform disassembly and subdisassembly operations more quickly. Moreover, this work could be completed with an economy analysis comparing the costs of recycling and disassembly against the value of recovered metals.

On the other hand, it is of great importance to analyze how disassembly and subdisassembly operations can enhance the recovery of critical metals used in electric cars. In this sense, the study of electric motors, power units, and batteries holds significant importance.

5. Conclusions

When cars reach the end of their life cycle, they are sent to a shredder where all car parts are mixed together. The subsequent recycling processes are highly effective in managing large volumes of ELVs and recovering steel and aluminum alloys. However, these processes are not suitable for recovering minor metals used in electronics. Based on the activities conducted for the two selected cars, the following conclusions can be drawn:

From a disassemblability perspective, vehicles are designed so that a significant portion of components can be replaced with new ones in case of a malfunction. However, in such cases, the repair process is the responsibility of the owner who incurs the repair costs. In contrast, in ELVs, the residual value of the vehicle is minimal, necessitating faster and more straightforward disassembly processes to facilitate the proper recycling of critical raw materials.

Regarding the analyzed parts, they are not frequently repaired. Although some professionals still repair combi instruments or generators, repairability is not cost-effective in most cases. This lack of repairability results in these parts not being designed for subdisassembly, making it challenging to obtain recycling fractions rich in high concentrations of critical raw materials suitable for specific metallurgical recycling processes.

Many electronic car parts often use fast joining methods like glues or thermal rivets to reduce manufacturing costs. However, this is counterproductive from a repairability and recyclability perspective, as subdisassemblability is often hindered.

Moreover, more communication and information sources between designers and recyclers should be available. Recyclers should have information from car manufacturers about the most valuable car parts from a raw materials perspective and how they should be disassembled or even subdisassembled quickly. Some current systems such as the International Dismantling Information System (IDIS) should incorporate this information.

In summary, vehicle designs prioritize fast and cost-effective manufacturing processes. However, this approach often conflicts with the disassemblability and recyclability of the product. The ongoing transition to new types of vehicles (electric, connected) necessitates a serious reconsideration of design, particularly given the supply chain issues and the recent scarcity of raw materials faced by the car manufacturing industry.

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Conflicts of Interest: Miquel Gimeno-Fabra was employed by the company Dynasty Motors and Marta Iglesias-Émbil was employed by SEAT S.A. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

Description of the cars used in the work.

Table A1. Vehicles used in the disassemblability process.

SEAT Leon model II—Manufactured on March 2007	
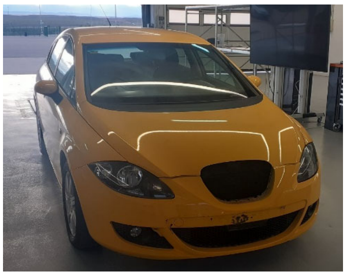	
Plate number 0610FMW	VIN number VSSSZZZ1PZ7RD78528

Table A1. *Cont.*

SEAT Leon model III—Manufactured on February 2015

Plate number	VIN number
7047JCW	VSSZZZ5FZFR111108

Appendix B

Thermodynamic rarity values of those metals used by vehicles selected.

Table A2. Thermodynamic rarity values (kJ/g) of the metals analyzed in this study.

Metal	Thermodynamic Rarity	Metal	Thermodynamic Rarity	Metal	Thermodynamic Rarity
Ag	8937	Ge	24,247	Ru	2,870,013
Al	661	Hf	32,364	Sb	487.9
As	427	Hg	28,707	Sm	732
Au	654,683	In	363,918	Sn	452
Ba	39.34	Ir	2,870,013	Sr	76.39
Be	709.9	La	336	Ta	485,911
Bi	545.6	Li	978	Tb	732
Cd	6440	Mg	145.7	Te	2,825,104
Ce	620	Mn	73	Ti	203
Co	11,010	Mo	1056	U	1090
Cr	40.9	Nb	4782	V	1572
Cu	348.4	Nd	670	W	8023
Dy	732	Ni	758	Y	1357
Er	732	Pb	41	Yb	732
Eu	732	Pd	2,870,013	Zn	196
Fe	32	Pr	873	Zr	2025
Ga	754,828	Pt	2,870,013		
Gd	4085	Rh	103,087		

Appendix C

Description of facilities and tools used for the disassemblability analysis.

Manual activities developed with vehicles were performed in MotorLand Aragon's facilities. The work area was constituted by a technical box of 300 m^2 equipped with specific tools. This workspace was equipped with the following materials: 4 × 2 m kitted workbenches (273-piece tools sets); solid and liquid residue discharge modules; a DT3600 scissor car lift; a Sicam SBM 135L wheel balancing machine; a Sicam Evo 628 SV1 tire changer; LED lights throughout the entire workspace; and an air compressor—7 bar. Figures A1 and A2 show the work area during disassemblability activities.

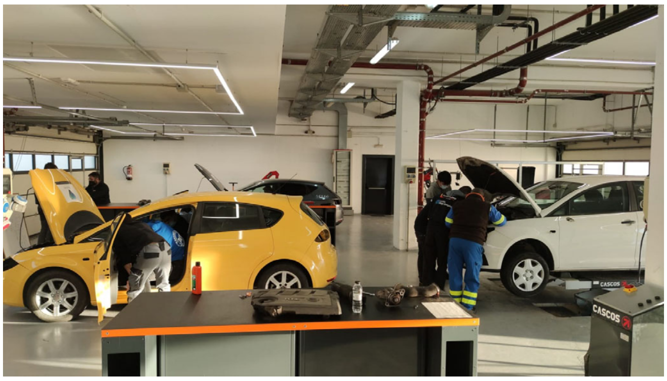

Figure A1. Work area used in disassemblability assessment.

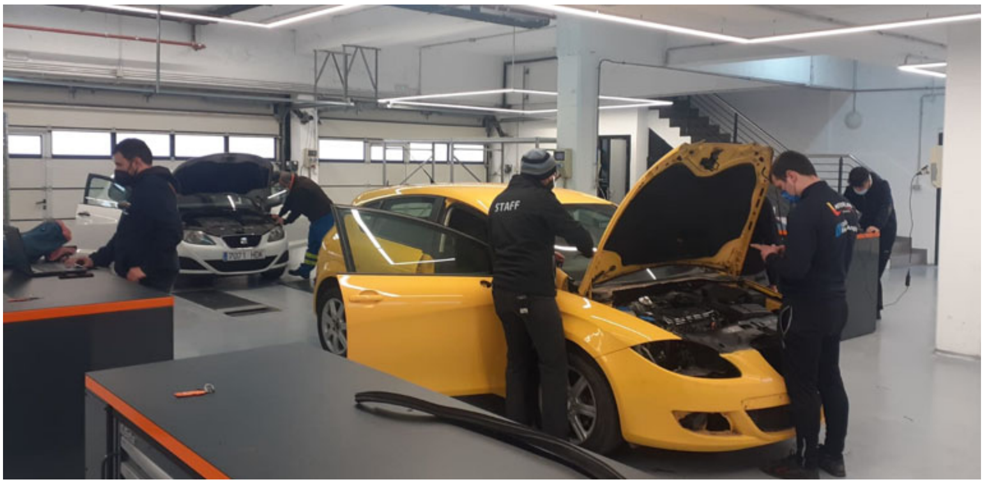

Figure A2. Work area used in disassemblability assessment.

References

1. Wells, P. Sustainable business models and the automotive industry: A commentary. *IIMB Manag. Rev.* **2013**, *25*, 228–239. [CrossRef]
2. OICA. Sales Statistics. Available online: http://www.oica.net/category/sales-statistics/ (accessed on 15 July 2016).
3. European Automobile Manufactures' Association. Vehicles in Use in Europe. 2023. Available online: https://www.acea.auto/files/ACEA-report-vehicles-in-use-europe-2023.pdf (accessed on 17 January 2024).
4. The International Council on Clean Transportation. Pathways to Decarbonization: The European Passenger Car Market 2021–2035. 2021. Available online: https://theicct.org/wp-content/uploads/2021/06/decarbonize-EU-PVs-may2021.pdf (accessed on 17 January 2024).
5. Hernandez, M.; Messagie, M.; De Gennaro, M.; Van Mierlo, J. Resource depletion in an electric vehicle powertrain using different LCA impact methods. *Resour. Conserv. Recycl.* **2017**, *120*, 119–130. [CrossRef]
6. Ortego, A.; Valero, A.; Valero, A.; Restrepo, E. Vehicles and critical raw materials. A sustainability assessment using thermodynamic rarity. *J. Ind. Ecol.* **2018**, *22*, 1005–1015. [CrossRef]
7. Riba, J.-R.; López-Torres, C.; Romeral, L.; Garcia, A. Rare-earth-free propulsion motors for electric vehicles: A technology review. *Renew. Sustain. Energy Rev.* **2016**, *57*, 367–379. [CrossRef]
8. Simon, B.; Ziemann, S.; Weil, M. Potential metal requirement of active materials in lithium-ion battery cells of electric vehicles and its impact on reserves: Focus on Europe. *Resour. Conserv. Recycl.* **2015**, *104*, 300–310. [CrossRef]
9. Andersson, M.; Söderman, M.L.; Sandén, B.A. Are scarce metals in cars functionally recycled? *Waste Manag.* **2017**, *60*, 407–416. [CrossRef]
10. European Commission. Study on the Critical Raw Materials for the EU 2023 Final Report. 2023. Available online: https://op.europa.eu/en/publication-detail/-/publication/57318397-fdd4-11ed-a05c-01aa75ed71a1/language-en (accessed on 4 December 2023). [CrossRef]
11. Ohno, H.; Matsubae, K.; Nakajima, K.; Kondo, Y.; Nakamura, S.; Nagasaka, T. Resources, Conservation and Recycling toward the efficient recycling of alloying elements from end of life vehicle steel scrap. *Resour. Conserv. Recycl.* **2015**, *100*, 11–20. [CrossRef]
12. Ohno, H.; Matsubae, K.; Nakajima, K.; Nakamura, S.; Nagasaka, T. Unintentional flow of alloying elements in steel during recycling of end-of-life vehicles. *J. Ind. Ecol.* **2014**, *18*, 242–253. [CrossRef]

13. Nickel Institute. *Recycling of Nickel-Containing Materials in Automobiles*; Nickel Institute: Toronto, ON, Canada, 2018.
14. Maurice, P.; Niero, M.; Bey, N.; Paraskevas, D. Resources, Conservation & Recycling Environmental screening of novel technologies to increase material circularity: A case study on aluminium cans. *Resour. Conserv. Recycl.* **2017**, *127*, 96–106. [CrossRef]
15. Iglesias-Émbil, M.; Abadías, A.; Valero, A.; Calvo, G.; Reuter, M.A.; Ortego, A. Criticality and Recyclability Assessment of Car Parts—A Thermodynamic Simulation-Based Approach. *Sustainability* **2023**, *15*, 91. [CrossRef]
16. Milojević, S.; Miletić, I.; Stojanović, B.; Milojević, I.; Miletić, M. Logistics of electric drive motor vehicles recycling. *Mobil. Veh. Mech.* **2020**, *46*, 33–43. [CrossRef]
17. Parsa, S.; Saadat, M. Human-robot collaboration disassembly planning for end-of-life product disassembly process. *Robot. Comput. Integr. Manuf.* **2021**, *71*, 102170. [CrossRef]
18. Rehal, A.; Sen, D. An Efficient Disassembly Sequencing Scheme Using the Shell Structure. *CAD Comput. Aided Des.* **2023**, *154*, 103423. [CrossRef]
19. Liu, H.; Hai, J.; Li, L.; Yin, F. An efficient disassembly process generation method for large quantities of waste smartphones. *Procedia CIRP* **2022**, *105*, 140–145. [CrossRef]
20. Ruiz-Pastor, L.; Mesa, J.A. Proposing an integrated indicator to measure product repairability. *J. Clean. Prod.* **2023**, *395*, 136434. [CrossRef]
21. Rodríguez, N.B.; Gabriel, C.; Gaha, R.; Favi, C. Analysis of disassembly parameters in repairability scores: Limitations for engineering design and suggestions for improvement. *Procedia CIRP* **2023**, *116*, 738–743. [CrossRef]
22. Cappelletti, F.; Rossi, M.; Germani, M. How de-manufacturing supports circular economy linking design and EoL—A literature review. *J. Manuf. Syst.* **2022**, *63*, 118–133. [CrossRef]
23. Favi, C.; Germani, M.; Mandolini, M.; Marconi, M. Includes Knowledge of Dismantling Centers in the Early Design Phase: A Knowledge-based Design for Disassembly Approach. *Procedia CIRP* **2016**, *48*, 401–406. [CrossRef]
24. Zahedi, H.; Mascle, C.; Baptiste, P. A conceptual framework toward advanced aircraft end-of-life treatment using product and process features. *IFAC-PapersOnLine* **2015**, *48*, 767–772. [CrossRef]
25. Sawanishi, H.; Torihara, K.; Mishima, N. A study on disassemblability and feasibility of component reuse of mobile phones. *Procedia CIRP* **2015**, *26*, 740–745. [CrossRef]
26. Germani, M.; Mandolini, M.; Marconi, M.; Rossi, M. An approach to analytically evaluate the product disassemblability during the design process. *Procedia CIRP* **2014**, *21*, 336–341. [CrossRef]
27. Sabaghi, M.; Mascle, C.; Baptiste, P. Evaluation of products at design phase for an efficient disassembly at end-of-life. *J. Clean. Prod.* **2016**, *116*, 177–186. [CrossRef]
28. Kroll, E.; Carver, B.S. Disassembly analysis through time estimation and other metrics. *Robot. Comput. Integr. Manuf.* **1999**, *15*, 191–200. [CrossRef]
29. Vanegas, P.; Peeters, J.R.; Cattrysse, D.; Tecchio, P.; Ardente, F.; Mathieux, F.; Dewulf, W.; Duflou, J.R. Ease of disassembly of products to support circular economy strategies. *Resour. Conserv. Recycl.* **2018**, *135*, 323–334. [CrossRef]
30. Milojevic, S.; Pešić, R.; Lukić, J.; Taranović, D.; Skrucany, T.; Stojanović, B. Vehicles optimization regarding to requirements of recycling example: Bus dashboard. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *659*, 012051. [CrossRef]
31. Giudice, F.; Kassem, M. End-of-life impact reduction through analysis and redistribution of disassembly depth: A case study in electronic device redesign. *Comput. Ind. Eng.* **2009**, *57*, 677–690. [CrossRef]
32. Peiró, L.T.; Polverini, D.; Ardente, F.; Mathieux, F. Advances towards circular economy policies in the EU: The new Ecodesign regulation of enterprise servers. *Resour. Conserv. Recycl.* **2020**, *154*, 104426. [CrossRef]
33. Romano, T.T.; Alix, T.; Lembeye, Y.; Perry, N.; Crebier, J.C. Towards circular power electronics in the perspective of modularity. *Procedia CIRP* **2023**, *116*, 588–593. [CrossRef]
34. Soh, S.L.; Ong, S.K.; Nee, A.Y.C. Application of design for disassembly from remanufacturing perspective. *Procedia CIRP* **2015**, *26*, 577–582. [CrossRef]
35. Smith, S.S.; Chen, W.H. Rule-based recursive selective disassembly sequence planning for green design. *Adv. Eng. Inform.* **2011**, *25*, 77–87. [CrossRef]
36. Go, T.F.; Wahab, D.A.; Rahman, M.N.A.; Ramli, R.; Azhari, C.H. Disassemblability of end-of-life vehicle: A critical review of evaluation methods. *J. Clean. Prod.* **2011**, *19*, 1536–1546. [CrossRef]
37. Desai, A.; Mital, A. Evaluation of disassemblability to enable design for disassembly in mass production. *Int. J. Ind. Ergon.* **2003**, *32*, 265–281. [CrossRef]
38. Ortego, A.; Valero, A.; Valero, A.; Iglesias, M. Toward Material Efficient Vehicles: Ecodesign Recommendations Based on Metal Sustainability Assessments. *SAE Int. J. Mater. Manuf.* **2018**, *11*, 213–228. [CrossRef]