Journal of Cleaner Production 513 (2025) 145725

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Evaluating the recyclability of electronic car parts through disassemblability, thermodynamic and metallurgical analyses

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ARTICLE INFO

Keywords:
Recycling
Resource efficiency
Strategic metals
Thermodynamics
Circular economy
Metallurgy

ABSTRACT

In the manufacturing of conventional cars, more than 50 different metals are utilized, many of which are categorized as critical or strategic. These metals are predominantly found in significant quantities within electronic car parts, necessitating specialized recycling methods for their recovery. However, conventional shredding processes often result in the downcycling of valuable metals into steel or aluminum alloys, or their disposal in landfills. To address this, a novel methodology is introduced, based on thermodynamic and metallurgical principles. It combines the Thermodynamic Rarity indicator with disassembly analysis and metallurgical process compatibility. By identifying valuable subparts and assessing dismantling costs, appropriate metallurgical processes can be designed to maximize the recovery of strategic metals. This methodology is demonstrated through three recycling scenarios— (1) shredding, (2) car dismantling, and (3) part disassembly— applied to the Combimeter and Infotainment system of a SEAT Leon Generation II model. Tailored metallurgical processes are proposed to recover steel, copper, and their compatible metals. The results highlight the potential of this approach for improving resource efficiency. For instance, dismantling the Combimeter achieves a Mineral Capital recovery of up to 59 %, while part disassembly marginally improves recovery for the Infotainment system by only 2 % compared to the dismantling scenario. Nonetheless, a limitation of the current processes is their inability to recover certain critical metals, such as tantalum. This work demonstrates how integrating thermodynamic and metallurgical insights can inform recycling strategies and enhance the recovery of critical and strategic metals in automotive electronics.

1. Introduction

The automotive sector stands out as one of the largest consumers of raw materials in the world (Hovorun et al., 2017). Therefore, the trend in sales will inevitably lead to increasing materials demand (Hernandez et al., 2017). In addition, the demand for cleaner, smarter and safer vehicles not only increases the materials needed, but also their variety (Andersson et al., 2017a; Ortego et al., 2018a). However, using a wide material diversity is not only an area of concern for electric, autonomous and modern cars, but also for conventional vehicles in stock (Urban mine platform, 2022). For example, a European hatchback segment C vehicle requires more than 52 different metals and metalloids (Ortego, 2019).

The variety of metals primarily stems from electronic subparts such as controllers, actuators, wiring, or sensors (Andersson et al., 2016; Andersson et al., 2019; Restrepo et al., 2017; Du et al., 2015). In fact, several studies have highlighted car electronics as a significant source of secondary strategic and/or critical metals (SCMs), being anticipated to constitute 50 % of the total car cost by 2050 (Chitkara et al., 2013). Beyond electronics, Du and Graedel evaluated various types of cars (combustion, hybrid and fully electric) in terms of rare-earth-using sub-parts (Restrepo et al., 2017; Du and Graedel, 2011). Additionally, Løvik et al. (2014) stated that SCMs are also used in aluminium alloys

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https://doi.org/10.1016/j.jclepro.2025.145725
Received 19 August 2024; Received in revised form 30 April 2025; Accepted 13 May 2025
Available online 14 May 2025

Abbreviations

Cm_h	Cost per man-hour
CMs	Critical Metals
DfR	Design for Recycling
EAF	Electric Arc Furnace, a type of furnace used in steelmaking. It uses an electric arc to melt scrap steel and other raw materials to produce new steel
EE	Electrical and Electronic components
ELV	End-of-Life Vehicles
EU	European Union, referenced in the context of critical metals classifications, such as tantalum being recognized as a critical metal
HSC	Software tool used to simulate chemical and metallurgical processes, focusing on thermodynamics and energy optimization
MARAS	Material Recycling and Sustainability, a consultancy company, which provides technology-based system solutions and knowledge in the field of recycling and resources, sustainability and circular economy
MISS	Material Information Sheet System
MC	Mineral Capital – A measure of the criticality of materials, calculated in terms of thermodynamic rarity and expressed in kJ or MJ
NMC	Nickel-Manganese-Cobalt, a type of lithium battery that uses a mixture of these three materials in its cathode. These batteries are commonly found in modern electric vehicles
P	Total labour cost
PCBs	Printed Circuit Boards – Components in electronic devices that house various metals critical for functionality, such as gold, copper, and palladium
pO_2	Partial pressure of oxygen, the effective concentration of oxygen in a system, such as in a reactor or a specific atmosphere. In metallurgy, pO_2 is critical because it influences chemical reactions and thermodynamic equilibria, especially in oxidation and reduction processes
SCMs	Strategic and/or Critical Metals
SEAT	Spanish Society of Touring Automobiles. SEAT S.A. – The only company that designs, develops, manufactures and markets cars in Spain. The multinational is also a member of the Volkswagen Group
TR	Thermodynamic Rarity
TRA	Thermodynamic Rarity of a specific subpart
TSL	Thermodynamic Slagging Layer, it refers to the slag layer (a mixture of impurities, residues, and other non-metallic components) that forms and is maintained in certain smelting processes, such as in EAF or in metal reduction processes in blast furnaces
Tw	Work time
USD	United States Dollar, mentioned in reference to the price of the metals
VW-Low Gen3 Front	Specific front suspension system used in Volkswagen Group vehicles built on the third-generation (*Gen3*) platform

and the steel car frame. Summarising, SCMs include rare earths in permanent magnets; tin in electronics; tantalum in capacitors; and semiconductors such as gallium or germanium in microchips. In addition, alloying elements like tungsten, vanadium, and niobium are contained in steel whereas magnesium or manganese – and sometimes scandium – are contained in aluminium. Also, the mass fraction of gold in automobiles, which is mainly found in integrated electronic controllers (Restrepo et al., 2017; Du et al., 2015), ranges from 0.2 g/t to 6 g/t. On the other hand, the mass fraction of Nd in automobiles, which is mainly found in embedded electric motors, can be around 300 g/t (Restrepo et al., 2017; Du et al., 2015). Finally, in disassembled electric motors and controllers in automobiles, the mass fraction of CMs (critical metals) can be several orders of magnitude higher (Restrepo et al., 2020). As result of the chemical analyses carried out by Widmer and his group, it is shown that the mass fractions of Co, Sn, Sr, Ta, Y, and Zr were dominant with >20,000 g/t in the selected EE (electrical and electronic) components and Ag, Ga, Mo, Sb, Sn, Sr, and Zr with >50 g/t in the analyzed shredder fractions (Widmer et al., 2015).

To ensure improved circularity of raw materials in the automobile sector, stricter measures are being implemented. For instance, European legislation regarding End-of-Life Vehicles (ELV) has recently been updated (European Commission, 2023), and it is anticipated that new regulations will soon be published to further promote a genuinely circular economy, in line with the objectives outlined in the European Green Deal (Ragonnaud et al., 2025). However, achieving this level of circularity remains a challenge, particularly concerning minor yet valuable metals (Andersson et al., 2017a). ELV recycling processes primarily focus on disassembling these car parts for potential resale, removing pollutants such as fuel or oil, recovering subparts like tires, batteries, and catalytic converters, and recycling metallic fractions such as steel or aluminium alloys (Andersson et al., 2017b).

Industrial facilities responsible for metal recycling are typically shredding plants, designed primarily to separate ferrous from non-ferrous fractions. These fractions are forwarded to specific metallurgical processes: ferrous materials to electric arc furnaces (EAF) for steel production, aluminium to remelters and refiners, and copper to smelters such as Top Submerged Lance (TSL) reactors or Top Blown Rotary Converters (TBRC). However, this process results in the downcycling of an important part of minor metals (Ohno et al., 2015) as shown in the Metal Wheel (Figure D.4; Appendix D; Supplementary Material 1), such as those employed in electronics or specific alloys. Consequently, these high-entropy processes result in the depletion of up to 25 % of the materials of a conventional car, measured in thermodynamic terms (Ortego et al., 2018a).

One strategy to mitigate the downcycling of minor yet valuable metals involves dismantling car parts that utilize these metals and subsequently applying specific recycling processes based on metallurgy (Iglesias-Émbil et al., 2023; Reuter and van Schaik, 2016).

For this purpose, the first step is to identify the car parts that contain those SCMs. Aiming to establish an objective classification of critical car parts, the authors of this work propose a method grounded in thermodynamics using the parameter Thermodynamic Rarity (Ortego et al., 2018; Calvo et al., 2018; Castro et al., 2004; Iglesias-Émbil et al., 2020; Ortego, 2019; Ortego et al., 2018; Valero et al., 2015). In contrast, prices of metals are highly volatile – for example, the price of tantalum, has increased more than 40 % in the last year – and critical raw materials lists vary depending on the country. This method has already been applied to combustion, hybrid and electric vehicles by (Iglesias-Émbil et al., 2020) and (Ortego, 2019), have demonstrated effectiveness compared to mass-based approaches.

The final step involves designing metallurgical processing infrastructures based on BAT (Best Available Techniques) to maximize the recovery of minor yet valuable metals. While vehicle recycling has been extensively explored, significant inefficiencies persist. Reuter et al. (2019) emphasize that current recycling practices often fail to achieve complete material recovery. This is constrained not only by thermodynamic limits, as argued by Valero and Valero (2014), but also by the physical and economic challenges of processing complex material mixtures. These constraints are further analyzed in relation to real system inefficiencies and the suboptimal performance of existing infrastructures (van Schaik and Reuter, 2010). From a systems perspective, studies such as Liu et al. (2023) and Valero et al. (2018) illustrate how the lack of infrastructure aligned with circular economy principles limits the effective recovery of critical and minor metals (Ignatenko et al., 2008). They argue for a paradigm shift towards metallurgy-led design, integrating thermodynamic viability with advanced process engineering. In this sense, BAT-aligned infrastructure upgrades become not only desirable but essential for closing material loops, especially for high-demand green technologies that depend on minor metals.

Despite the extensive work undertaken in previous research, a clear methodology for determining whether a car part should be dismantled, selectively disassembled, or recycled with the bulk material is still lacking. For example (Ohno et al., 2015), identified the issue of downcycling, particularly concerning steel-alloying elements, and proposed sorting scrap steel for targeted recycling. Similarly (Xu et al., 2019), showed that selective dismantling of printed wire boards and rear window heating wires can drastically increase the recovery of precious metals such as Au, Ag, Pt, Pd, and Rh. As an additional application, (Reuter et al., 2018) highlighted the benefits of component separation in the recycling of electronic devices such as the Fairphone.

Several studies, such as those by (Kamateros and Abdoli, 2023) and (Shahjalal et al., 2022), propose automated disassembly roadmaps for batteries and electronics, emphasizing systematic dismantling to maximize material recovery. Nevertheless, in practice, disassembly remains costly, time-consuming, and requires specialized tools.

Different approaches have been proposed to support dismantling decisions, mainly categorized into mass-based assessments, economic evaluations, and thermodynamic indicators. Mass-based methods prioritize components with a high relative concentration of critical materials (Binnemans et al., 2013), but may overlook strategic elements present in low quantities. Economic evaluations are often unstable due to the volatility of metal prices and can result in inconsistent dismantling strategies. (Lèbre et al., 2017; Otterbach and Fröhling, 2025). In contrast, the Thermodynamic Rarity indicator offers a stable, physically grounded measure of material criticality, integrating geological scarcity and processing efficiency based on the Second Law of Thermodynamics (Seabra & Caldeira-pires, 2020).

Traditional metallurgical experimental methods for metal separation are effective but require significant resources and time. In contrast, simulation methods, such as those proposed by (Palav et al., 2024), use computational models to design efficient metal recovery processes from e-waste, minimizing the need for extensive physical trials. Others studies, such as (Nagel, 2018), developed a model for eddy current separation, demonstrating how simulations can optimize the recovery of non-ferrous metals. Integrating these simulations into our methodology would enable an objective, resource-efficient evaluation of automotive part recyclability, minimizing experimental testing.

In this paper, we propose a methodology to evaluate the recyclability of car parts using three key concepts: Thermodynamic Rarity, disassemblability and metallurgic recycling simulations to achieve global and objective way of measuring how impactful and convenient different activities and scenarios in the context of recycling industry can be. We demonstrate its application to two parts. Since this method does not rely on experimental tests, it can be extrapolated to any part of any vehicle and holds the potential to become the standard in the automotive industry for determining the appropriate actions for specific parts. Furthermore, it can help the automotive industry to decide which parts should be redesigned following the principles of eco-design. By combining thermodynamic analysis, disassemblability assessment, and metallurgical recycling simulations, our methodology offers, for the first time, a more holistic view of material criticality and recyclability. This represents an essential step toward sustainable decision-making in vehicle design and end-of-life management.

2. Methodology

2.1. Case study description

SEAT Leon Generation II was selected as the case study for this analysis. Reasons are its representativeness and age. It was the brand's best seller during its manufacturing period of time and is classified as segment C and hatchback body, being one of the most sold types of cars in Europe. Regarding age, the analyzed car generation span a production time period from 2005 to 2012 and is currently achieving the end of the life (ELV) or will do it in the coming years.

Two parts were chosen for the recyclability assessment: the Combimeter and the Infotainment system. The selection of these car parts stems from their prior identification as critical subparts based on their material usage from a thermodynamic perspective (Ortego et al., 2018b). In a previous research endeavour, the identification of these subparts was facilitated by two thermodynamic indicators: Mineral Capital [kJ] and specific Thermodynamic Rarity [kJ/g], that are discussed later. The former metric aids in identifying subparts that possess a high concentration of valuable metals and are consequently deemed significant from a thermodynamic standpoint.

Examining the material composition (Fig. 1), the Combimeter weighs 829 g, with only 213 g (26 %) comprising metals, while the remaining portion is plastic. Conversely, the Infotainment system weighs 1973 g, with 1587 g (80 %) being metal and the remainder plastic.

2.2. Thermodynamics for measuring the criticality of raw materials

To assess metal criticality and recycling performance efficiently, the physical parameter known as Thermodynamic Rarity (TR) is utilized. The methodology for its calculation has been presented in earlier works (Ortego et al., 2018; Valero et al., 2015; Amini et al., 2007). A brief overview will be given to enhance understanding. Specific Thermodynamic Rarity seeks to quantify the intrinsic value of minerals by considering two key factors: (1) their natural abundance and (2) the net energy expenditure for extraction and processing. This approach integrates the strengths of both mass and economic-based methodologies, providing a strictly physical indicator that is universal, objective, and more stable than monetary-centric approaches. Thermodynamic Rarity is calculated as the sum of two terms: the Exergy Replacement Cost and the Embodied Exergy Cost. The first term is linked to the cost saved by nature's inherent advantage. That is, the supply of minerals concentrated instead of dispersed in the Earth's crust. The second term refers to the energy required for mining, mineral extraction and concentration up to refining.

When a specific raw material in a product is not recovered properly, it is lost. This loss implies extracting more from the Earth's crust.

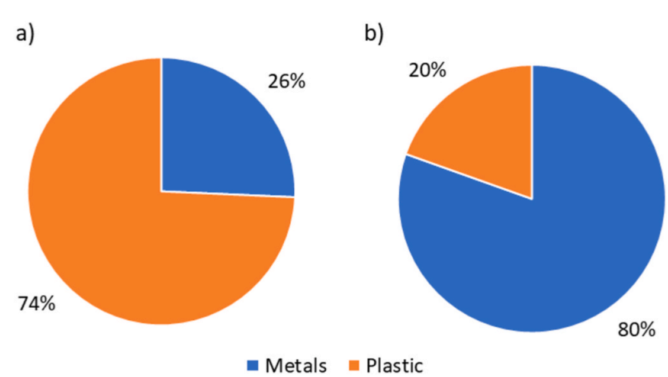


Fig. 1. Material mass composition for the Combimeter (Fig. 1a) and the Infotainment system (Fig. 1b). Data obtained from SEAT Information System. Total metal mass of Combimeter 26 % and Infotainment system 80 %. Total plastic mass of Combimeter 74 % and Infotainment system 20 %.

Thermodynamics, through Rarity indicator, allows to evaluate the Mineral Capital lost. Specific Thermodynamic Rarity values for the metals analyzed in this study are included in Appendix A of Supplementary Material 1 (Table A.1) being such values as weighting factors for each metal.

2.3. Work flow

A methodology based on three different recycling cases was designed and applied to carry out this work. This method was structured into seven steps, as shown in Fig. 2. The first step involves collecting the material composition of car parts. This information comes from an internal SEAT IT system called Material Information Sheet System (MISS), which is common to the whole Volkswagen group and similar to the systems owned by other car manufacturing groups. Through this system, the composition of each part was known at different levels, with each level representing a subdivision of the immediately higher level. Level 1 corresponded to the whole car part, while subsequent levels represented the subparts derived from the higher level.

To verify the digital information from MISS, parallel work was conducted with physical car parts. Subparts were disassembled, weighed, and cross-referenced with the information from MISS. This step was crucial for identifying and rectifying any data errors or inconsistencies (Step 2). Throughout this process, the use of tools (both standard and non-standard) and the time required for disassembly were recorded for further economic evaluation. Details of this information can be found in Appendix B in Supplementary Material 1.

Subsequently, in Step 3, we conducted a calculation to determine the material composition of the car part and its subparts. Using this information, the Thermodynamic Rarity of each subpart (TR_A) was computed (Step 4). This was achieved by summing the products of the mass of each metal *(m_i)* and its specific Thermodynamic Rarity *(tr_i)* value for all metals comprising a car component (Equation (1)).

$$TR_A = \sum_{i=1}^{n} m_i \cdot tr_i \qquad \text{(eq.1)}$$

In Step 5, a material characterization of the disassembled subparts was conducted to determine the optimal recycling route in each case. These subparts were classified into the following four recycling groups: (1) Ferrous metals; (2) Non-ferrous metals excluding Aluminium; (3) Aluminium; and (4) Plastics. This classification aimed to facilitate a high degree of metal recovery in specific recycling processes based on metallurgy. As elucidated by (Iglesias-Émbil et al., 2023), the current state of the art in industrial recycling processes necessitates selecting one of these fractions as a starting point. Details of the subparts and recycling routes classification can be found in Appendix C in Supplementary material 1.

Next (Step 6), the recyclability of each car part was analyzed considering the following three cases.

Case 1. (Shredding): This represents the current situation, where dismantling these parts is not mandatory, and therefore they undergo fragmentation and post fragmentation processes to obtain ferrous and non-ferrous scrap.

Case 2. (Car dismantling): In this scenario, the part is removed from the vehicle and subjected to a single metallurgical process designed for copper and compatible metals through the so-called Cu route (which was selected as the most optimal based on expert know-how and compositional characteristics (van Schaik and Reuter, 2024).

Case 3. (Part disassembly): The main part is disassembled into subparts, and thereafter, the most suitable recycling route is applied to each subpart based on its composition. For this purpose, there are two recycling routes available: (1) the Cu route and (2) the Steel route, aimed at recycling steel and compatible metals. Energy recovery has also been included as an optional processing route.

The reason for considering these two (or three) recycling routes lies

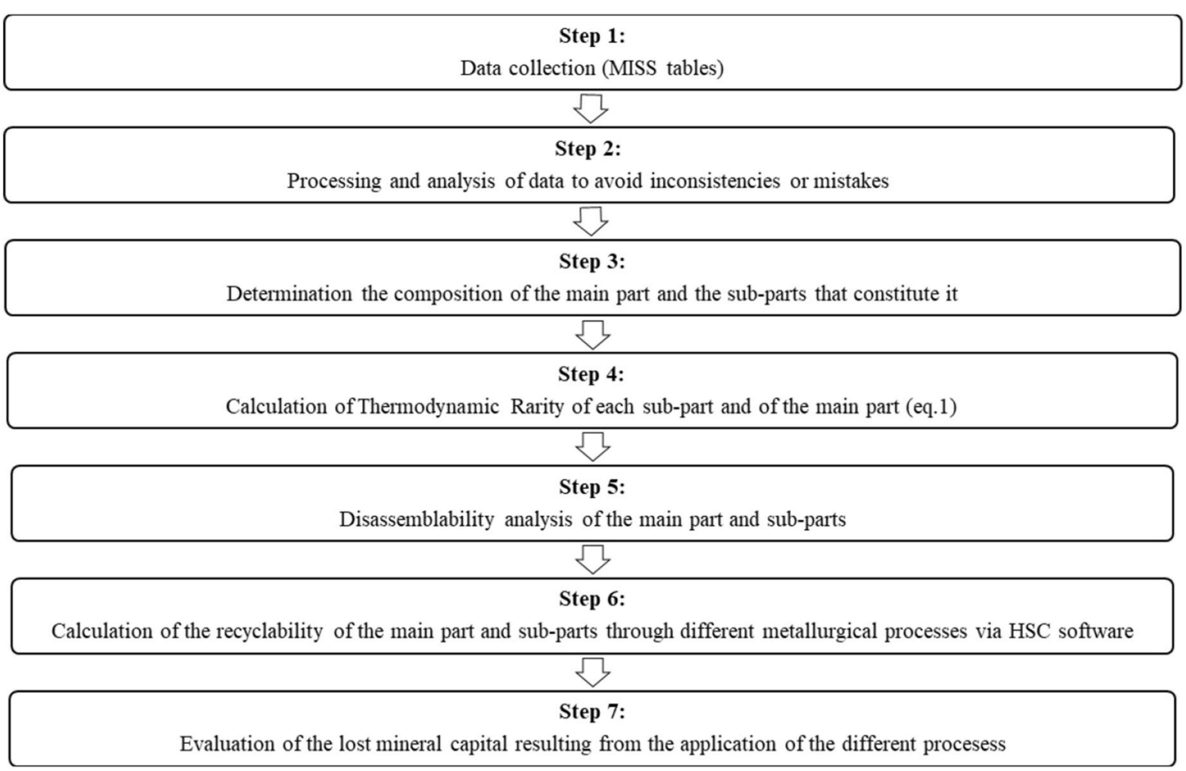


Fig. 2. Diagram illustrating the steps in the methodology employed in this project, from data collection to the evaluation of lost mineral capital. The methodology encompasses three distinct recycling scenarios: shredding, dismantling, and disassembling.

in the composition of the selected parts, as well as in the properties of metals. For instance, although aluminium recycling is commonly addressed in the literature, aluminium is a highly reactive and ignoble metal that tends to form alloys with other metals during melting, which can complicate the separation and recovery of valuable elements and increase processing costs. Once the cases were defined, a simulation-based approach was used to determine the recycling rate of the different car parts, as shown in figure D.1. It shows that each car part is processed in a segment of the Metal Wheel for optimal recovery of materials and energy, where each segment in the Metal Wheel is representing a full metallurgical recycling infrastructure for the processing of the different (base and associated) metals. Detailed flowsheets for each of the processing routes are underlying this approach. Due to the complex mixture of materials in the car parts, it is not possible to define a most suitable processing option upfront, therefore, for each car part, based on its composing material composition, the two or three best options are selected based from the full metallurgical recycling infrastructures. By doing this, the most optimal recycling route can be selected based on the achieved recycling results. The flowsheet model used for this simulation-based approach is based on industrial economically viable processing. The assessment and underlying calculations as performed by the application of rigorous and physics-based process simulation model include the complex interlinkages of functional materials in the car parts as well as all chemical transformation processes in the reactors in the system model in versatile flowsheet simulation modules.

Finally, in Step 7 the loss of Mineral Capital associated to each case was calculated. This last stage is explained in the next section.

2.4. Recyclability assessment: thermodynamics and metallurgy

The recyclability of a car part (η A), measured in thermodynamic terms via Thermodynamic Rarity, is calculated using Equation (2):

$$\eta_A(\%) = \left(\frac{TR_A^f}{TR_A^0}\right) \times 100 \qquad \text{(eq.2)}$$

Where TR^0 is the Thermodynamic Rarity of the metals contained in the car part to be analyzed and TR^f is that of the metals recovered after the recycling process applied. In this sense, the loss of Mineral Capital (L) is calculated by replacing the corresponding factor $\left(\frac{TR^f}{TR^0}\right)$ by $\left(1 - \left(\frac{TR^f}{TR^0}\right)\right)$, as in Equation (3).

$$L_A(\%) = \left(1 - \left(\frac{TR_A^f}{TR_A^0}\right)\right) \times 100 = L_A = 100 - \eta_A \qquad \text{(eq.3)}$$

The method applied in this step is based on existing background developed by Reuter and van Schaik and discussed in the (Handbook of Recycling, 2024). To calculate the fraction of each metal recovered is calculated using the industrial software platform HSC Chemistry Sim® 10 (www.metso.com) was utilized. This software enabled the design of recycling models based on metallurgical processes. By inputting the composition of the car parts obtained from MISS and the custom-designed recycling model, HSC calculates the material, energy and exergy flows generated as a result of the recycling process. The metallurgical processes designed followed the Cu route and Steel route, with the recovery rates determined based on the affinities with the metallurgical processes designed for copper or steel, respectively. Schemes of the recycling processes designed are provided in Appendix D in Supplementary Material 1. In order to perform realistic and reliable recycling assessment, it must be noted that the chemical composition for each part, including organic components, is required. This implies in other words, that the complete *"mineralogy"* of the product must be available as is usual when simulating and optimizing metallurgical processes and flowsheets, see (van Schaik and Reuter, 2014; Reuter et al., 2018).

The flowsheet model is based on thermochemistry and calculates mainly on a Gibbs Free Energy Minimization approach, gleaning activity coefficients and various details from industrial experience, FACT Sage (FactSage SoftwareTM, 2001), knowledge on all the hydro- and pyro-metallurgical as well as energy recovery reactor technology that maximize the recovery of material, element, alloy, energy recovery, while minimizing the dissipation of exergy.

The simulation model is based on a 20 t/h operating, thus industrially acceptable scale in order to be able to estimate realistic material and energy flows throughout the complete flow sheet comprising of 189 reactors connected by ca. 1000 streams (Figures D5 to D8). All streams are presented in their full compound resolution i.e., all the many compounds (in this model ca. 1000) are presented in their full solution chemistry reality (both ideal and non-ideal solutions). This enables the calculation of the recovery of highly refined final products: elements, compounds, alloys, etc.

Once the recoveries of the elements—whether as pure metals, refined compounds, specific alloys, etc.—that can be reused in the same functional capacity in the recycled part or module have been established, the link to the rarity assessment can be made. For more details on the development of simulation-based design for recycling and rarity estimation, please refer to the summary table (Table G.1 in Appendix G of Supplementary Material 1).

The composition of the targeted car parts is annexed in the Appendix file. This list of compounds has been defined based on the full composition of both car parts, as well as including all compounds and phases that are created in the recycling processing of these car parts in the different processing routes as included in the model.

2.5. Economic evaluation

A brief cost-analysis was carried out to compare the different cases. The time required for dismantling and disassembling the car parts was recorded, and the labour cost per man-hour was assumed to be the Spanish average of 41€/hour (LAUSAN, 2023). Using these values, the total labour cost (P) of dismantling and disassembling the car parts was calculated by multiplying the man-hour cost (C_{mh}) by the worktime (t_w) (Equation (4)).

$$P = C_{mh} \cdot t_w \qquad \text{(eq.4)}$$

The prices of the metals were obtained from different sources, using the average values from 2022, as 2023 prices were significantly affected by geopolitical volatility. These values are listed in Appendix E of Supplementary Material 1. It should be noted that metal prices are subject to strong fluctuations due to factors such as supply and demand, geopolitical instability, and energy costs. This inherent volatility can influence the outcome of the analysis, particularly when assessing economic viability.

3. Results and discussion

3.1. Mineral capital measured in terms of Thermodynamic Rarity

Table 1 shows the 10 metals with highest Mineral Capital. Even though the mass of the Infotainment system is almost six times that in the Combimeter (1513 g and 213 g respectively), their Mineral Capital are quite similar: 600 MJ and 700 MJ for the Infotainment system and the Combimeter, respectively. This is a good example of how this method assigns a criticality value that considers not only the quantity of the resource (measured in mass), but also its physical scarcity.

In both cases, tantalum and gold combined are the main contributors to the Mineral Capital values, with 66 % and 89 % over the total for the Infotainment system and the Combimeter, respectively. It must be noted that these metals together comprise less than 1 % of the mass of each car

Table 1
Material composition and Mineral Capital of the 10 metals with the highest Thermodynamic Rarity contribution in the Combimeter and Infotainment system. Metals ordered by their contribution to the Mineral Capital measured in terms of Thermodynamic Rarity.

Infotainment System					Combimeter				
Metal	Mass (g)	Mass share among metals (%)	MC[a] in part (kJ)	MC share (%)	Metal	Mass (g)	Mass share among metals (%)	MC in part (kJ)	MC share (%)
Ta	0.7	0.04	$3 \cdot 10^5$	38	**Au**	0.6	0.3	$4 \cdot 10^5$	53
Au	0.4	0.02	$2 \cdot 10^5$	30	**Ta**	0.5	0.2	$2 \cdot 10^5$	36
Pd	0.1	<0.01	$2 \cdot 10^5$	18	**Pt**	0.02	<0.01	$4 \cdot 10^4$	6
Fe	1415	89	$5 \cdot 10^4$	5	**Al**	14	6	$91 \cdot 10^3$	1
Al	66	4	$4 \cdot 10^4$	5	**Ag**	1	0.4	$7 \cdot 10^3$	1
Cu	80	5	$3 \cdot 10^4$	3	**Cu**	19	9	$7 \cdot 10^3$	1
Ag	1	0.1	$7 \cdot 10^3$	1	**In**	0.01	<0.01	$4 \cdot 10^3$	1
Ru	0.01	<0.01	$6 \cdot 10^3$	1	**Sn**	6	3	$3 \cdot 10^3$	0.4
Co	0.3	0.02	$3 \cdot 10^3$	0.4	**Sb**	3	1	$1 \cdot 10^3$	0.2
Sn	7	0.4	$3 \cdot 10^3$	0.3	**Nd**	1	0.4	$6 \cdot 10^2$	0.1

[a] MC: Mineral Capital measured in terms of Thermodynamic Rarity.

part but thermodynamics highlights their importance from a physical point of view.

On the contrary, iron presents a different scenario. In the case of the Infotainment system unit, iron exhibits a low Mineral Capital measured in terms of Thermodynamic Rarity (5 %), despite comprising 89 % of the metal content by mass. Furthermore, in the Infotainment system unit, more than 99 % of the mass is attributed to only three elements: iron, copper, and aluminium. Conversely, the Combimeter demonstrates a more diverse composition, with five elements contributing more than 1 % of the part's mass. Iron is not included in the Combimeter section of Table 1 because its rarity does not rank among the top ten, despite its mass representing more than half of the total metal mass.

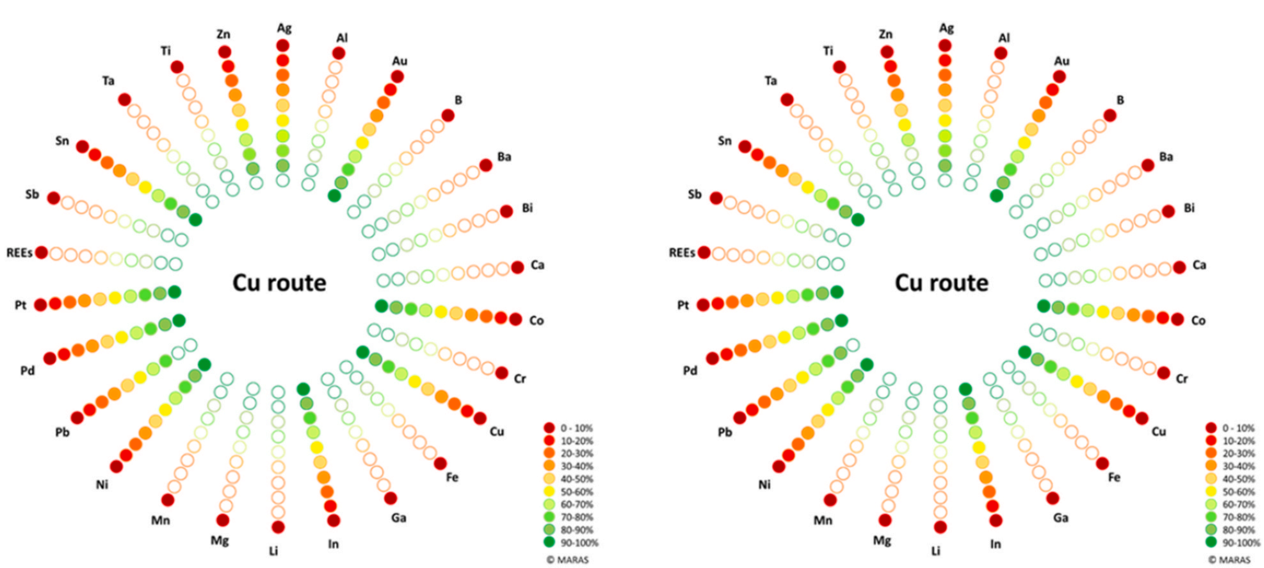
Noteworthy to mention is that previous analyses (Ortego, 2019; Ortego et al., 2018) state that more than 50 % of the Mineral Capital measured in terms of Thermodynamic Rarity of the whole car is attributed to iron and aluminium. This is easily explained by the fact that they constitute more than 95 % of the metallic mass of the car. In contrast, gold and tantalum collectively contribute to barely more than 2 % of the total rarity of the car, with their mass contribution being lower than 0.001 %. This implies that the two parts analyzed in this study serve as significant sources of these two metals and should be considered important if there is an interest in recycling gold or tantalum, being the latter classified as a critical metal by the EU (Grohol, 2023). Details of the sub-parts of the Combimeter and Infotainment system, along with their primary metals based on Mineral Capital measured in terms of Thermodynamic Rarities, are provided in Appendix F in Supplementary Material 1.

3.2. Recyclability assessment

As explained in section 2.4, the recovery of each metal at the end of the metallurgical recycling processes was simulated. Figs. 3 and 4 shows the recovery rates of the different metals in both car parts and under metallurgical recycling cases (2 and 3). The graphs represent the recovery rates obtained for each metal and recycling route.

Fig. 3a and b depict the recovery rate of different metals in Case 2 (car part dismantled from the car) for the Combimeter and Infotainment system, respectively. Since the most significant metals could be recovered via the Cu route, both parts were assumed to undergo recycling through that process. The other reason for selecting the Cu route for Case 2, is that there are too many disturbing elements in the Case 2 part, resulting in a very impure iron alloy if this route would be followed. In the charts, dark red colour indicates negligible or null recyclability of the metals, while dark green signifies complete circularity in recycling. Upon dismantling and recycling as a single car part, gold, cobalt, copper, indium, nickel, palladium, platinum, and tin are almost fully recovered from both parts.

Fig. 4a and b illustrate Case 3 (part disassembled) for the



a) Case 2 – Combimeter b) Case 2 – Infotainment system

Fig. 3. Recycling rates obtained from HSC in Case 2 (van Schaik and Reuter, 2024). Recovery of each metal at the end of the metallurgical recycling processes.

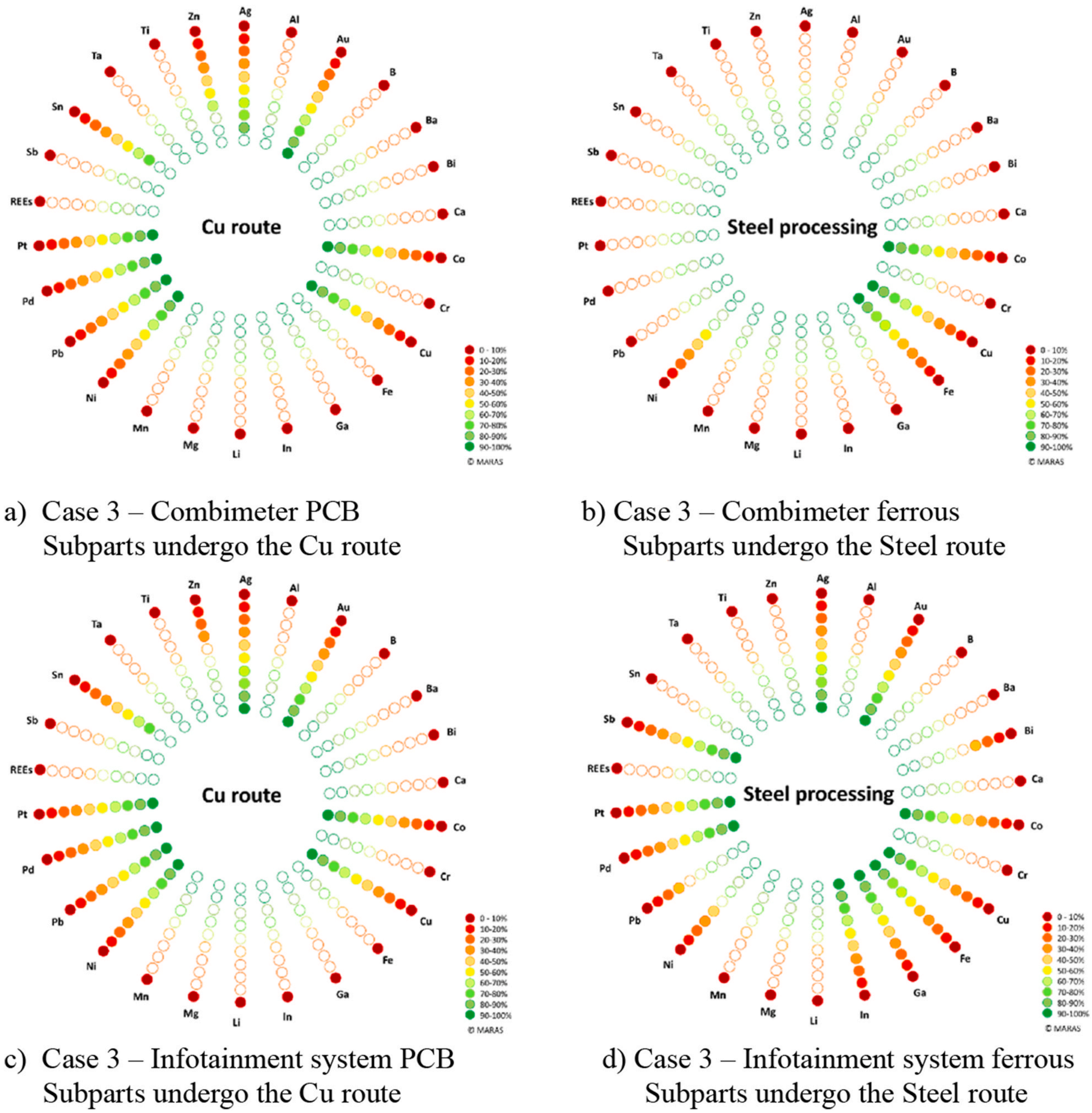


Fig. 4. Recycling rates obtained from HSC in Case 3 (van Schaik and Reuter, 2024). Recovery of each metal at the end of the metallurgical recycling processes. Note that this refers to elemental recovery within the metallurgical flowsheet, not functional recycling. Elements that are recovered as unintended constituents in bulk alloys (e.g., unwanted elements in steel) are also included.

Combimeter. In this scenario, the PCBs are recycled through the Cu route (Fig. 4a), resulting in complete recovery of silver, gold, cobalt, copper, nickel, lead, palladium, and platinum. Conversely, ferrous parts (Fig. 4b) are recycled through the steel route, with cobalt, copper, and iron being recovered with total circularity.

Fig. 4c and d shows Case 3 for the infotainment system, highlighting the recovery rate of the PCBs and the disassembled ferrous subparts, respectively. It is worth noting that the steel route in the Infotainment system case (Fig. 4d) appears to be a viable method for recovering the dismantled ferrous parts, as the level of unwanted elements are reduced/minimised by further dismantling allowing to produce a cleaner iron alloy, than would be the case for the total dismantled part. This is also the reason why for the total dismantled parts, the Fe route is not a good option. Also, minor metals such as silver, gold, gallium, indium, palladium, platinum, antimony cobalt or copper are considered unwanted elements in the iron alloy produced, and their presence is accounted for in the provided percentages of the iron alloy fraction but does not represent functional recovery. Consequently, in terms of Mineral Capital, these elements are not effectively recovered and cannot be reintroduced into the circular economy cycle.

These results can be compared with those obtained in other similar studies on the recovery of material resources in other electronic devices (Reuter et al., 2018; Reuter et al., 2019). For instance, in a smartphone model (Fairphone 2), materials such as gold, copper, silver, cobalt, nickel, palladium, platinum, gallium, indium and zinc can all be recovered in high percentages (80–98 %), and modularity promotes their recovery. In our case, for the car parts, the above metals are also recovered in percentages between 80 and 100 % (Figs. 3 and 4), except for gallium and indium, which, due to metallurgical incompatibilities and their low content in car parts, cannot be recovered. Furthermore, magnesium, in the case of the Fairphone, can be recovered at rates of 90 %–92 % in shredding cases, where magnesium is liberated through dismantling and sorted from other materials into high-quality recycled forms. However, in our study this metal is completely lost in all cases. Equally, tantalum, being a critical metal, is very difficult to recover in both smartphone and car cases unless the parts containing them are removed and processed separately.

As an example, indium is an interesting element to recover because its recovery depends on if there is indium in feed and if there is enough of it, and especially if the pO2 in the reactor and the flow of gas through it, is in the correct window as observed in Figure D.3. Appendix D in Supplementary Material 1 provides a more detailed explanation of the conditions under which indium is recovered.

3.3. Recyclability in terms of Thermodynamic Rarity

3.3.1. Dismantling-dependence of recovered mineral capital

Adding the thermodynamic perspective to the results of the metallurgical processes (Step 7 in Fig. 2), we obtain the recyclability in terms of recovered Mineral Capital. Fig. 5 shows the values for each recycling case. As it can be seen, the shredding of the car results in a low recovery of the Mineral Capital of each part, which is especially low – almost negligible – for the Infotainment system. When the parts are dismantled from the car, the recyclability increases up to 59 % and 49 % for the Combimeter and the Infotainment system, respectively, mainly because of the enhanced recovery of gold, platinum and palladium. This represents a high improvement with a simple and economic process, as will be discussed later.

In Case 3 (disassembly into subparts), the total recyclability only marginally increases, rising from 49 % to 51 % in the Infotainment system. In Case 2 (dismantling), this part undergoes the Cu route entirely. In Case 3, after dismantling and disassembly, the controller PCB, heat sink, and the entire VW-Low Gen3 Front without frame and drive undergo the Cu route, whereas the metal housing and frame are directed to the steel route. In terms of Mineral Capital, iron contributes 5 % to this car part, so its recovery represents an improvement. However, in the case of the Combimeter, not only does the recyclability not improve, but it slightly worsens. The total recyclability shows a minimal variation from Case 2 to Case 3. This reduction is due to the small quantity of ferrous fraction in this part. Only the screws were made of steel, which also contained nickel, incompatible with the steel route but compatible with the Cu route. Consequently, the gain in terms of Mineral Capital due to iron recovery does not offset the loss of nickel. In scenario 2 (dismantling), the Combimeter undergoes the Cu route entirely, while in scenario 3 (disassembly into subparts), after dismantling and disassembly, the PCBs follow the Cu route, and the metal screws are directed to the steel route.

Finally, it should be mentioned that disassembly was only effective for the Infotainment system, although the improvement was only 2 % compared to Case 2. This fact demonstrates that disassembly for the purpose of applying additional metallurgical processes is only effective for components containing a high percentage of iron.

3.3.2. Assessment of mineral capital lost by metal

Fig. 6 shows the loss of Mineral Capital for each case and component analyzed, indicating the contribution of each metal to this loss. In this way, the most important metals that are not recovered in each case are identified. The three cases contemplated for the Combimeter and Infotainment system are represented. In Case 1 (Fig. 6a and b), where the only metal recovered would be iron, it can be observed how gold and tantalum constitute the major Mineral Capital loss from the Combimeter and Infotainment system, respectively, which is consistent with those metals being the biggest contributors to the Mineral Capital measured in terms of Thermodynamic Rarity of the parts (Table 1). The remaining Mineral Capital loss is mainly composed of platinum in the Combimeter and palladium, aluminium and copper in the Infotainment system.

When the car parts are dismantled, Case 2 (Fig. 6c and d), it can be seen that the relative loss of tantalum increases because the amount of tantalum lost remains constant, while the loss of other metals, such as gold or palladium, decreases. This is because tantalum cannot be recovered through the Cu route. Conversely, as gold is recovered by that process, its loss of Mineral Capital (relative to the total loss) decreases by 8 times for the Combimeter and 11 times for Infotainment system. In the former part, it is also observable how platinum is recovered in its entirety. In the latter, palladium loss – as gold – is also reduced by 11 times and copper is recovered in its entirety. In both parts, the relative importance of aluminium in the capital loss increases when the parts are disassembled and recycled through the Cu route, as this metal is negligibly recovered by this process. The same happens with iron in the Infotainment system. This is because Aluminium will always go to slag in steel and copper processing. In recycling as aluminium is associated with all other elements will dissolve some elements and contaminate the aluminium. This metal rapidly oxidizes during steel recycling, forming oxides that end up in the slag and cannot be recovered as metal due to its strong affinity for oxygen (Fisher and Barron, 2019).

On the other hand, aluminum, in non-ferrous metal recycling processes such as copper, also combines with oxygen to form oxides that end up in the slag. Furthermore, due to its chemical and thermodynamic

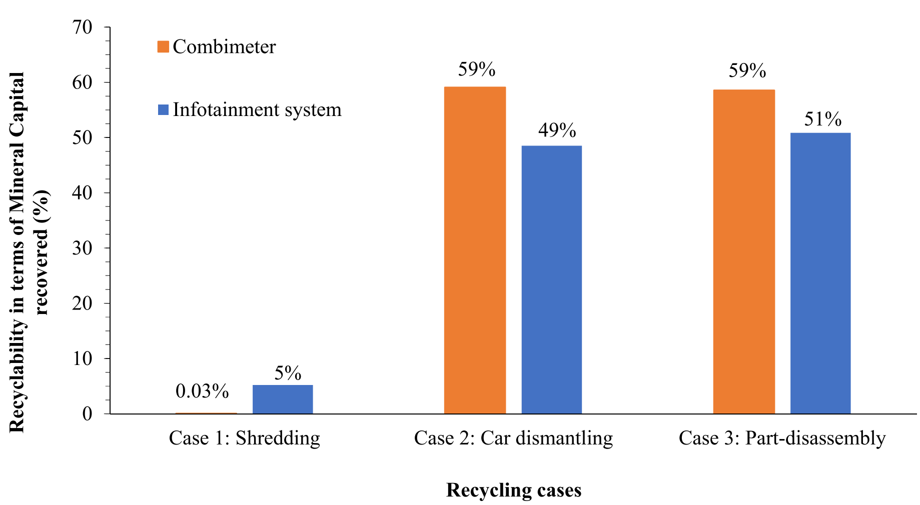


Fig. 5. Recyclability of both parts considering the different cases. The largest amount of Mineral Capital recovered of Combimeter is 59 % (Case 2). The largest amount of Mineral Capital recovered of Infotainment system is 51 % (Case 3).

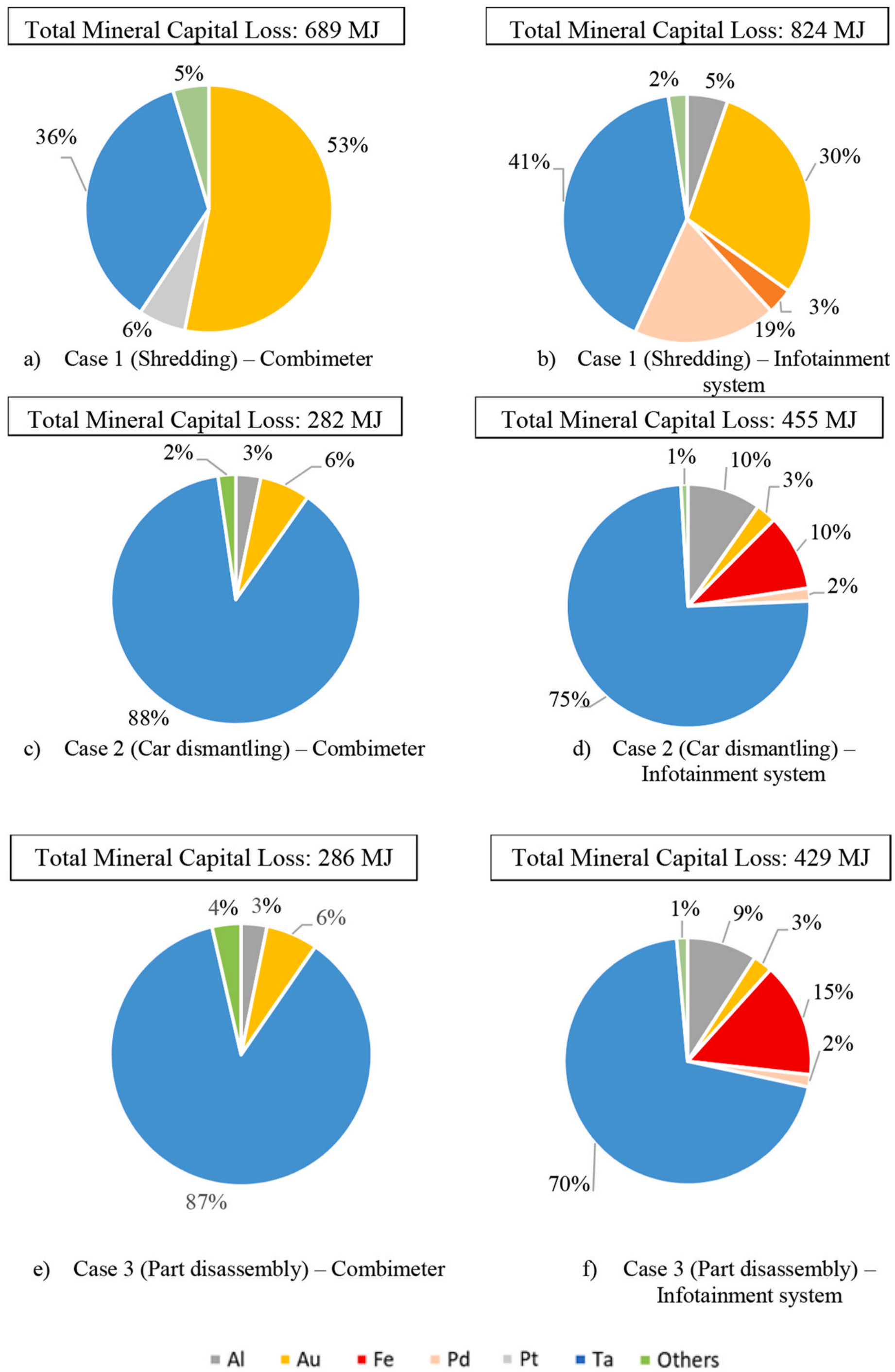


Fig. 6. Mineral Capital loss by metal in the three cases for the Combimeter and the Infotainment system. The largest amount of Total Mineral Capital Loss occurs in Case 1 for both car parts: 689 MJ for the Combimeter and 824 MJ for the Infotainment system.

properties, aluminum is not easily recovered in these processes and contaminates the alloys when mixed with other elements (Piatak and Ettler, 2021).

Finally, in Case 3 (Fig. 6e and f), we observed similar values of the metals with respect to Case 2 in all metals except iron, which increases 1.5 times with respect to dismantling for the Infotainment system. The Mineral Capital loss of the less critical metals is also slightly increased in both car parts. In both parts (either in Case 2 or 3), the Mineral Capital loss Case 2 is mainly due to the incompatibility between the recovery of tantalum and the applied metallurgical processes oriented to recovery of copper and steel.

This is due to the fact that, in order to improve the recyclability of the Infotainment system, one of the sub-parts containing most of iron (the controller, with 542 g of iron) has been directed to the metallurgical processing route oriented to the recovery of copper instead of steel.

3.4. Economic analysis of dismantling and disassembling

The economic value of the recovered metals in each case (and for each part) was calculated by multiplying their recovered mass by their market price in the year 2023 (Fig. 7).

On the other hand, the dismantling and disassembling labour costs

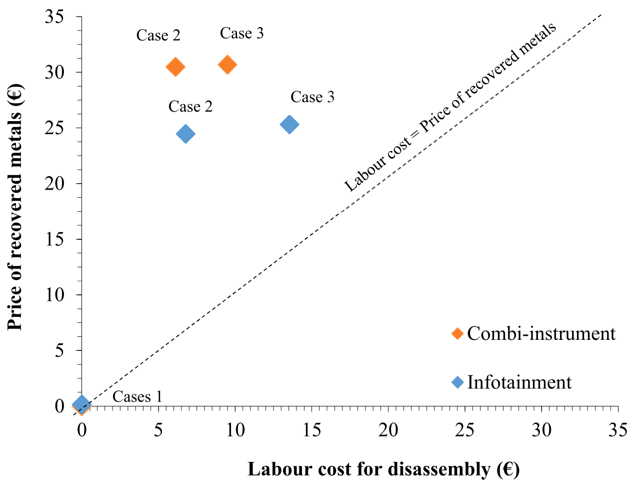


Fig. 7. Added labour cost of dismantling or disassembling. Assessment of the three cases: shredding, dismantling and disassembling for the Combimeter and Infotainment system.

for each car part were calculated using equation (4). The dismantling time of the Combimeter and the Infotainment system, respectively, are 0.15 h and 0.17 h (6 € and 7 € of labour costs), whereas the disassembly took 0.23 h and 0.33 h (labour costs of 9 € and 14 €) for the cited car parts.

In Case 1, labour time and cost were considered to be negligible. Under these assumptions, the recovered economic value was approximately 31€ for both the Combimeter and the Infotainment system. For the Infotainment system, this value was 24€ in Case 2 and 25€ in Case 3. The discrepancy in values primarily stems from the higher amount of gold present in the Combimeter (0.6 g vs. 0.4 g). These results suggest that a maximum of 25€ additional revenue could be obtained from recycling the Combimeter and 18€ additional revenue from recycling the Infotainment system. Notably, Case 2 (dismantling) yielded the greatest economic benefit for both parts, as the additional recovered economic value of the metals did not justify the required disassembly time and its corresponding additional cost. It is important to note that the dashed line in Fig. 7 represents the point at which labour costs equal the current price of recovered metals. However, it should be emphasized that logistic and recycling costs have not been taken into account, and these costs are not negligible. In all studied cases, labour costs are lower than the price of recovered metals, suggesting that conducting dismantling or disassembly operations may be advantageous based on the economic value of the recovered metals. To further support this assertion, logistic and recycling costs should be evaluated and included.

In the analyzed car parts, precious metals have the greatest economic potential for recovery, in contrast to what happens – for example – in smartphones (Bookhagen et al., 2020). The gold content in the Combimeter and infotainment system is 0.6 g and 0.4 g respectively, but constitutes the highest value with a current share of approximately 95 % of the total value of all metals measured, followed by silver (2 %) for the Combimeter. In the case of the infotainment, gold represents 77 % of the total value of all metals measured, followed by palladium (15 %).

Both in this study and in that of Bookhagen et al. previously mentioned, it is revealed that most of the Strategic and Critical Materials (SCMs) are concentrated in the electronic components of the devices. In the case of the smartphone, the printed circuit board (PCB) contains 90 % of the measured gold, 98 % of copper 99 % of palladium, 86 % of indium, and 93 % of tantalum. Meanwhile, in this research, the Combimeter's PCB contains almost 100 % of the measured gold, 91 % of copper, 0 % of palladium, 25 % of indium, and 100 % of tantalum, whereas the infotainment's PCB contains almost 100 % of the measured gold, 99 % of copper, 100 % of palladium, 100 % of indium, and 100 % of tantalum. As a result, the automotive sector and other industries are considering the dismantling of their products before recycling or disposal to ensure efficient resource recovery. In this respect, Table G.1, included in Appendix G of Supplementary Material 1, compares the methodologies, assessment bases, and calculations of various articles addressing the recyclability of automobiles and other technologies.

It must be noted that, if the industry trend is towards miniaturisation, reducing the electronic devices in size would reduce the number of precious metals and therefore the economic benefit could be compromised (Almeida et al., 2012). This miniaturisation would imply more difficulty in the metal recovery process. The final recovered material mass would be lower and therefore the economic benefit obtained would also be lower. The parts assessed constitute an old model of a combustion vehicle, but the evolution of the composition of the parts over time would have to be considered.

4. Conclusions

This work is novel in its integrated approach, combining disassemblability assessment of car parts with a rigorous, physics-based recycling analysis grounded in Thermodynamic Rarity and Gibbs Free Energy simulations. To our knowledge, this is the first study to apply these methods consecutively to evaluate recyclability from both a design and material recovery perspective. As a case study, an analysis of the recyclability of two electronic parts of a conventional car was carried out, using the concepts of Mineral Capital measured in terms of Thermodynamic Rarity and metallurgical compatibilities applied to recycling processes. This combined methodology was implemented under three different dismantling scenarios showing the impact on the recoverability rates of the metals from the car parts. The recovery rates were calculated with software simulations using two different metallurgical recycling routes: copper and steel.

The most important metals in terms of mass are aluminium, copper and iron in both car parts. However, when considering the physical criticality, measured through Thermodynamic Rarity, the most important elements in the Infotainment system and the Combimeter are gold and tantalum. These metals contribute to 66 % and 89 % of the total Mineral Capital measured in terms of Thermodynamic Rarity in the Infotainment system and Combimeter, respectively.

Dismantling the car parts from the car before recycling significantly boosts Mineral Capital recovery, increasing it from nearly non-existent to 59 % in the case of the Combimeter and 49 % in the Infotainment system. However, disassembling the car parts into subparts only yields a marginal increase in recovered Mineral Capital, with just a 2 % increment in the case of the Infotainment system and no increment at all in the case of the Combimeter.

From an economic standpoint, dismantling the parts from the car allowed the recovery of more than 25€ worth of metals (mainly gold) at a labour expense of no more than 7€. However, disassembling the parts into subparts resulted in a doubling of the labour cost in the Infotainment system and a 60 % increase in the case of the Combimeter, with virtually no greater economic benefit associated to the greater amount of metals recovered. To provide a comprehensive view of the cost-effectiveness of the dismantling and disassembly recycling process, the cost of the reverse logistics and recycling processes required to implement circularity in the automotive sector must be taken into account. Some of these costs include the transport of end-of-life devices to processing plants, as well as the energy and reactants needed to recover the relevant metals.

The results obtained at the theoretical level demonstrate that recycling technologies are available for the recovery of metals from complex products such as electronic car parts. Coupling these technologies with a simple activity of dismantling car parts can significantly increase the recovery rates of Strategic and/or Critical Metals. Nevertheless, even though cars are a great source of Strategic and/or Critical Metals, they are not currently recycled in a functional way. This issue persists with conventional cars, and with the advent of future electric and connected cars, the problem is expected to become even more severe. Therefore, for future research, it would be essential to examine the effectiveness of the proposed model in recovering Strategic and/or Critical Metals from parts of electric cars, such as permanent magnets, electronic boards, or battery cells. Additionally, the potential impact of automation on enhancing disassembly processes should also be investigated.

We aim to establish the methodology presented in this article as a reference for future studies on the recyclability of critical materials in the automotive industry and other technological goods.

CRediT authorship contribution statement

Samuel Alcoceba-Pascual: Writing – original draft, Investigation, Data curation. **Abel Ortego:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Nicolás I. Villanueva-Martínez:** Writing – original draft, Data curation. **Antoinette van Schaik:** Software, Investigation. **Markus A. Reuter:** Writing – review & editing, Software, Investigation. **Marta Iglesias-Émbil:** Writing – review & editing, Resources, Methodology. **Alicia Valero:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This research work has been carried out within the framework of the following projects.

This publication is part of the RESTORE Project (PID2023-148401OB-I00) funded by MICIU/AEI/10.13039/501100011033 and by FEDER, EU; the RELOAD Project (Ref. VEC-020100-2022-52) and Project Future: Fast Forward (Ref. VEC-010000-2022-1) funded by the Ministry of Industry, Trade and Tourism, and by the European Union through the Recovery, Transformation and Resilience Plan (PRTR); and the TREASURE Project funded by the European Union's Horizon 2020 research and innovation program under grant agreement nº. 101003587.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.145725.

Data availability

Data will be made available on request.

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